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1 Introduction

The objective of the MIT project is to improve the interoperability of fingerprint systems using minutiae-based templates. For this purpose the project is conducting an evaluation of interoperability. This evaluation shall address:

- measurement of the level of interoperability achievable; e.g.:
  - what is the loss of performance from interchange of minutiae data as opposed to using proprietary formats?
  - what is the loss of performance due to inter-operation of components from different suppliers when interchanging minutiae data?
- reveal problem cases, to allow suppliers to improve consistency and performance of minutiae extraction and comparison algorithms. e.g.:
  - what types of data, data-format options, etc. cause the fewest interoperability problems?
  - what improvements in interoperability are achieved after
- development of conformance and performance testing methodologies to simplify the processes for assessment and certification of interoperability.

These aspects require a precise specification of the criteria by which interoperability will be assessed, including *inter alia*, the input and output options for the biometric components processing fingerprint minutiae records, the levels of performance required, and the methods for interpreting results as showing whether or not components are interoperable.

While there are no agreed definition or metric for interoperability of biometrics it is clear that measurement of interoperability encompasses:

- **absolute performance** (i.e. the levels of performance achieved when components from different suppliers interoperate);
- **relative performance** (i.e. differences in performance from using different data formats, or different components);
- **sufficiency** of a standard interchange format, quantifying the loss of performance relative to proprietary data formats (or other standard formats);
- **substitutability** of components (i.e. determination of whether we substitute a system component with a different version or one from a different supplier without an unacceptable deterioration in performance); and
- **conformance** of components in reading and writing data records of the data interchange standard.

This document provides a view (agreed by project partners) on the interoperability criteria to be considered within the MIT project. These criteria of minutiae interoperability will determine the specification for the data to be collected and tests to be conducted in the MIT project. As the project progresses, and results become available, these criteria will be revised and further developed.

2 Aspects of fingerprint minutiae interoperability

Interoperability is about the ability of different subsystems to work effectively together to achieve a required level of performance for a given application. A statement of interoperability needs to give details for each of these aspects.

In this section we give consideration to the subsystems, performance measures, applications, standards, etc. relevant to interoperability of fingerprint systems based on minutiae, i.e. characteristic points of the dermal ridges. As necessary, the MIT project's decisions are recorded restricting the scope of the aspects of interoperability to be considered within the project. Such limitations in scope are necessary for the practical application of interoperability testing.

2.1 Subsystems dealing with (or affecting) minutiae templates

In general, a biometric system consists of a variety of subsystems: sensors for data acquisition; subsystems for transmission and storage of data; algorithms for feature extraction and for comparison against stored templates; subsystems for making decisions based on comparison scores and thresholds; as well as those parts of the system handling the application for which there was a requirement for biometric recognition. It is the sourcing of these subsystems from different suppliers that gives rise to the need for standards to help ensure interoperability, as well as methods to validate that, through using such standards, the desired performance levels can be achieved.

This Minutiae template Interoperability Testing project is primarily concerned with the interoperability issues that are impacted by the use of fingerprint minutiae templates, i.e. by storing minutiae records for future comparison. In terms of subsystems, this means that we are mainly interested in interoperability between algorithms that extract minutiae records from fingerprint images (*minutiae extraction algorithms*), and algorithms that compare the stored minutiae templates with other minutiae records to determine whether they stem from the same or different fingers/people (*minutiae comparison algorithms*). The use of fingerprint minutiae otherwise has little impact on other subsystems of the biometric system. Nevertheless, there will be some dependency on the fingerprint sensors used for data acquisition, since fingerprints may need to be of sufficient quality and size to enable reliable minutiae extraction and comparison. Indeed, aspects such as fingerprint resolution need to be encoded in the minutiae template.

minutiae extraction:

- *input:* a fingerprint image, in an appropriate format
- *output*: a minutiae record, (appropriately formatted)

Minutiae extraction might also be integrated with the fingerprint capture process, or the process of segmentation of individual fingerprints when several fingerprints are acquired in a single "slap".

minutiae comparison:

Depending on the accuracy requirements of the application, prints of one, two, etc., up to ten fingers may be compared.

There are various modes for minutiae comparison: (i) verification, involving a one-to-one comparison between standard minutiae records (ii) verification involving comparison of a standard minutiae template against a proprietary record (or fingerprint images); or (iii) identification, involving a one-to-many search against a database of minutiae templates.

Verification

- *input:* two (appropriately formatted) minutiae records corresponding to the reference and recognition fingerprint sets
- *output:* a similarity score indicating a level of resemblance of the two fingerprint sets with respect to the used comparison algorithm

Verification (minutiae template to proprietary record comparison)

- *input:* minutiae template corresponding to the reference fingerprint set, and set of images corresponding to the recognition fingerprint set.
- *output:* a similarity score indicating a level of resemblance of the two fingerprint sets with respect to the used comparison algorithm

Identification

- *input:* a database of minutiae records of reference fingerprint sets, and a minutiae record corresponding to the recognition fingerprint set
- *output:* a candidate list with similarity scores

Minutiae comparison might also be integrated with the processes of minutia extraction, segmentation, or imaging of the recognition fingerprint

The project shall focus on testing interoperability between **minutiae extraction** and **minutiae comparison** subsystems with respect to fingerprint data collected using a specified set of fingerprint sensors.

(For example, the project shall not attempt to certify fingerprint sensors as being interoperable with these algorithms nor to determine minimum requirements on image size, resolution, grey-level depths of sensors, and the like.)

Sensors being used for data collection to be specified in WP2, are to include a high quality sensor for "slap" images, and a good quality sensor for single fingerprint "flat" images.

2.2 Standards applicable to minutiae extraction and comparison

2.2.1 Standards for fingerprint minutiae data

There are several closely related national and international standards for the data interchange of fingerprint minutiae data, [ANSI/INCITS 378], [ANSI/NIST-ITL 1-2000, Type 9] [DIN V66400] and [ISO/IEC 19794-2].

MIT will consider interoperability using the fingerprint minutiae data interchange formats standardised under ISO: ISO/IEC 19794-2: Information technology – Biometric data interchange formats – Part 2: Finger minutiae data

Options within ISO/IEC 19794-2 are summarised at Annex A. In deciding which options within this standard should be tested, it is noted that many options record the same data in a

different syntactic format, and interoperability problems are likely to be similar for these equivalent formats.

Options of 19794-2 to be tested. Further details to be decided in conjunction with vendors.

1-finger record format

1-finger compact card format

Options must be supported by 2 or more vendors.

2.2.2 Standards for fingerprint images

The project shall not focus on fingerprint sensors, but shall use collected fingerprint images as input to the minutiae extraction algorithms. It is desirable that these input images should conform to an appropriate standard. The options available are [ANSI/INCITS 381], [ANSI/NIST-ITL 1-2000, Type 4] and [ISO/IEC 19794-4].

Workpackage 2 decided to record images following the ANSI/NIST standard, which is well supported by existing tools and systems. (It is desirable that the fingerprint database collected within the MIT project does not use equipment or algorithms from the MIT vendors.) See [MIT-D2.1]

2.3 Types of interoperability

basic interoperability of two minutiae extraction subsystems with regard to a comparison subsystem: The comparison subsystem is able to process templates stemming from both minutiae extraction subsystems.

- data format interoperability: The subsystems should use the same data formats.
- interface interoperability: The subsystems should be able to exchange data (e.g., using BioAPI).

performance-based interoperability of two minutiae extraction subsystems with respect to a comparison subsystem: In addition to basic interoperability, the comparison subsystem does also achieve a sufficient performance in terms of error rates when comparing templates from the two minutiae extraction subsystems. (The amount of performance loss that would be acceptable, compared to a system where all templates stem from the same minutiae extraction subsystem, must be specified).

This project is primarily concerned with measuring and improving performance-based interoperability. Nevertheless, basic interoperability is a necessary pre-requisite to performance-based interoperability.

2.4 Types of application and performance requirements

Within the project, consideration of applications should be focussed on those with an interoperability requirement, i.e. applications where it is either inevitable, or there is a strong requirement that subsystems from different sources will have to interoperate. These tend to be large-scale and public applications, such as those involved in e-passports, visas, or identity cards. (Criminal justice AFIS systems currently use fingerprint images, and are not

sufficiently limited by either efficiency or privacy considerations to require a move to minutiae-based systems.)

For such large-scale civil applications, the accuracy requirements tend to be fairly stringent in order to ensure that the systems are both secure, and efficient in comparison to existing non-biometric methods. For verification, results to date show that at least two fingerprints would be required for a minutiae-based system to achieve error rates of FMR < 0.1%, FNMR < 1%. Indeed error rates lower than this would typically be desirable. For these type of applications it is quite likely that enrolment can be conducted using a high quality fingerprint scanner, certified to FBI Appendix F (such as the Smiths Heimann LS2 check sensor used in WP2). However, there are likely to be a greater number of verification stations, which may therefore deploy lower quality sensors in order to make cost savings. Thus we may have to consider that the system has to process higher and lower quality data, high quality for enrolment, and lower quality for verification.

Testing low error rates will require a large database of representative data (especially large if identification performance is to be considered). It can also be useful to produce a smaller database of "difficult" data on which systems are more likely to disagree on, as sharing such data and results can assist vendors in improving the interoperability of their algorithms.

Verification based on 1 fingerprint

It is useful to test interoperability of single fingerprint verification, as this enables comparison of MIT results against those of the MINEX and ILO trials.

Verification based on 2 fingerprints

> ***Target: 2-finger verification performance:*** **FRR < 0.5% at FAR < 0.01%**
>
> **These values are set to require an improvement in performance over that attained in the MINEX trial. The criterion may need adjustment (or augmented with further levels of interoperability) after the first phase of testing in WP5, when it will be clearer how difficult the collected data sets. (E.g. do proprietary algorithms perform with error rates well below these bounds?)**

Identification

While performance of 10-fingerprint identification is operationally relevant, we note that the largest database size we can reach within the MIT project is of the order of 10,000 people, rather than millions as is more common for such applications. An operationally realistic identification performance might be to achieve a False-positive identification-error rate (FPIR) of below 1% against a database of 1 million. Scaling back the database to 10,000 people means we should be targeting an FPIR of below 0.01% (1 in 10,000), an error rate which is at the limit of detection in a dataset allowing 10,000 identifications, and any measurement made within MIT would have a high degree of uncertainty. Consequently it was decided that there would be limited value in testing systems in identification mode.

2.5 Scenarios for use of minutiae templates

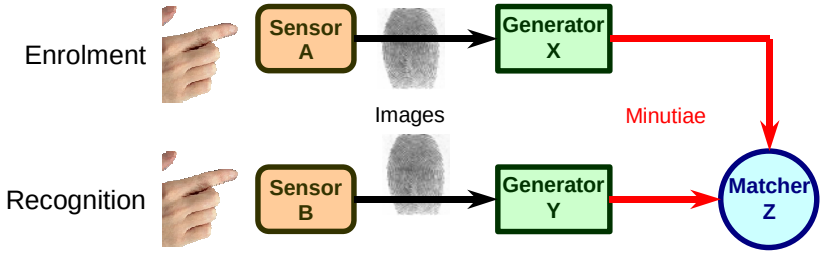

Figure 1. General scenario for minutiae interoperability

The general scenario for interoperability, depicted in Figure 1, may require consideration of five separate subsystems: the sensors for enrolment (A) and for recognition (B), the minutiae extraction algorithms (generators in the figure) for enrolment (X) and for recognition (Y), and the minutiae comparison algorithm (Z) (matcher in the figure). In most cases, however, there will not be such a diversity of subsystems, as often sensors will be paired with minutiae extraction algorithms, or minutiae extraction algorithms with comparison algorithms. Moreover, as the focus of the project is on minutiae extraction and comparison, the decision has been taken that the MIT will not test a wide variety of different sensors, but will collect fingerprint databases using representative good quality fingerprint scanners (Smiths Hiemann LS2 check, and Crossmatch Verifier 300 USB V2.0). This reduces the dimensionality of the interoperability tests proposed.

The following scenarios are considered the most relevant for assessment in MIT.

- For comparison against previous evaluations, MIT should conduct a test in a similar scenario.

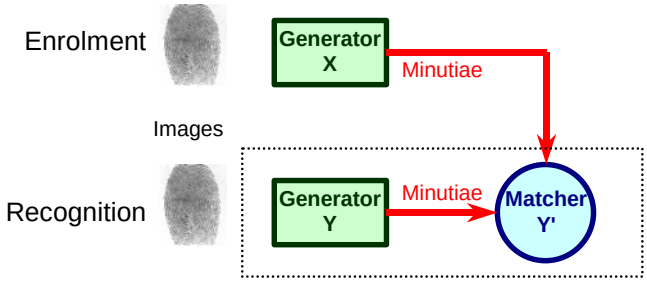

Figure 2. NIST MINEX Scenario 1, and also ILO Interoperability Testing Scenario

Figure 2 depicts the NIST MINEX Scenario 1, which is also the scenario used in the ILO interoperability tests. MIT should test in this scenario in addition to any others so that there are some tests to help in understanding whether there are any systematic differences in results between MIT tests and MINEX tests. Here recognition is made using minutiae extraction and comparison algorithms from the same supplier (developed to work together), though data interchange between these subsystems at recognition is required to use the standard data interchange format. However, there is often not a strict operational requirement that the recognition data must be interchanged using the standard minutiae format, which leads to MIT consideration of the next scenario.

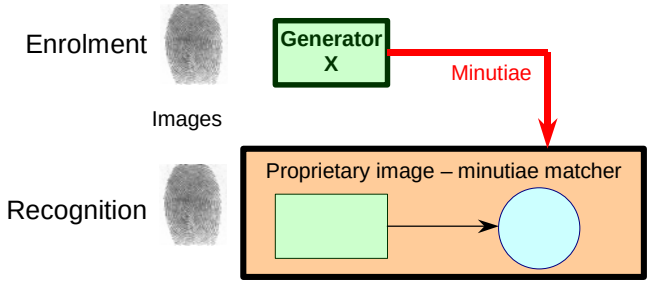

Figure 3. Scenario for minutiae to image matching

- Figure 3 depicts a scenario not included in MINEX (applicable, for example, in the case of template-on-card scenarios). Here, the stored biometric reference is a minutiae record in a standardised format, but the sample to be compared can be presented and processed in an entirely proprietary manner. This may be operationally more relevant than NIST MINEX scenario 1 (Figure 2). (A performance comparison between these two scenarios may indicate whether image to minutiae matching is significantly more accurate than minutiae to minutiae matching.) The inverted configuration, in which the reference template and matcher are bound in a proprietary manner, and the sample to be compared is presented as a minutiae record may also be operationally relevant, for example in case of match-on-card scenarios.

  We may also wish to consider sub-scenarios (a) where the enrolment and recognition images are both from high quality sensors, and (b) where the enrolment image is from a high quality sensor, but the recognition image is from a cheaper sensor.

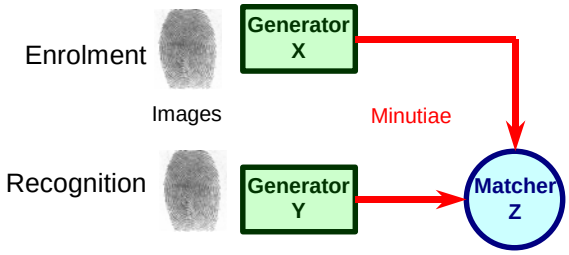

Figure 4. NIST Scenario 2 – applicable for centralised biometric comparison

- Figure 4 depicts the NIST MINEX Scenario 2, in which the minutiae comparison is not combined with minutiae extraction from the same supplier at either enrolment or recognition. This scenario is most relevant to applications such as identification where the biometric comparison is centralised.
- We also wish to consider sub-scenarios (a) where the enrolment and recognition images are both from high quality sensors, and (b) where the enrolment image is from a high quality sensor, but the recognition image is from a cheaper sensor.

2.6 Performance measures for minutiae extraction and comparison

Performance requirements for any application can be quite diverse: ease of use, throughput speeds, size of the stored biometric reference, may be relevant in addition to the accuracy of biometric recognition. Moreover, the input data, as well as the level of accuracy required can vary quite considerably between applications which may range from access control for a small number of employees, to national scale identity systems with tens or hundreds of millions of enrolled citizens.

In the case of minutiae extraction and comparison algorithms, performance will normally be considered in terms of the incidence of matching errors (causing false acceptance or false rejection errors in the case of verification, or false-positive and false negative identification errors in the case of identification) as well as cases where the extraction algorithm is unable to process the acquired image, or where the comparison algorithm is unable to process the extracted minutiae.

Failure to process rate for minutiae extraction ($FTP_{EXTRACT}$): Proportion of fingerprint images for which the minutiae extraction algorithm does not generate a conformant minutiae record.

Failure to process rate for minutiae comparison ($FTP_{COMPARE}$): Proportion of comparisons between minutiae records conforming to the standard, where the minutiae comparison algorithm returns a processing error rather than a matching score.

False match rate (FMR): Proportion of comparisons between (conformant) minutiae records from different individuals where the comparison algorithm returns a comparison score within the range for declaring a match. (The denominator of this fraction excludes failure-to-process cases)

False non-match rate (FNMR) Proportion of comparisons between (conformant) minutiae records from the same fingers & person where the comparison algorithm returns a comparison score outside the range for declaring a match.(The denominator of this fraction excludes failure-to-process cases)

False accept rate (FAR): Proportion of combined extraction-comparison processes between fingerprints from different people, where a comparison score is returned within the range for declaring a match. (The denominator of this fraction includes failure-to-process cases.)

False reject rate (FRR): Proportion of combined extraction-comparison processes between fingerprints from the same person/presented fingers, where a comparison score is returned within the range for declaring a match is not returned. (The denominator of this fraction includes failure-to-process cases.)

Interoperability performance measures will be based on the transactional error rates (i.e. FAR, FRR) of single-attempt transactions (i.e., without retries) as it is appropriate to include the extraction and comparison failures as well as the matching errors.

2.6.1 Decision thresholds: Fixed or source-varying[1]; Pre- or post-result calibration

A **fixed threshold** means that, when analysing the similarity scores of a particular comparison subsystem, the same threshold is used for determining match/non-match decisions regardless of the source of fingerprint data or minutiae extraction algorithm used.

A **source-varying threshold** means that the decision threshold of the same decision subsystem can vary dependent on the data source or the minutiae extraction

[1] Use of fixed vs source-varying thresholds is discussed at length in the NIST MINEX report [NISTIR7296].

algorithm. This allows the threshold to be adjusted so that all interoperating subsystems are achieving, say, the same FAR. This is convenient for analysis, otherwise specifying acceptable performance criteria is more complicated, since both FRR and FAR can float. However, it should be noted that the data interchange format standard does not properly allow recording of the minutiae extraction algorithm identifier, and the capture device type ID field would have to be usurped to do so. During normal operation, in general, the threshold is source-independent. Setting the threshold to a source-dependent value would only be possible for sources whose influence on the similarity scores is known.

Post-results threshold calibration means we readjust the threshold to that which delivers, say, the highest acceptable FAR, and then need only compare FRR values.

Pre-results threshold calibration means that the decision threshold must be set prior to collecting test results. Operationally, pre-calibration is required, but this complicates testing in requiring additional data for calibration, and requiring both FAR and FRR to be considered in analysis.

The comparison subsystems under test should return (for test purposes only) the similarity score of each attempt, so that pre-results threshold calibration is not needed. A decision about whether certification should use pre- or post-results threshold calibration (or fixed or source-varying threshold) can be further investigated. This aspect may then change for the second phase of testing.

2.7 Factors influencing minutiae template interoperability

Interoperability problems may be due to

- differences in the minutiae extraction and comparison subsystems: e.g. different skeleton and tangent methods in the feature extraction algorithms, different interpretations of the minutiae type “other” defined in [ISO/IEC 19794-2], different treatment of “noise” in fingerprint images.
- The extent of such differences may vary depending on properties of the fingerprint images, e.g., due to different sensors, different quality of acquired images, different grey-level depths, different image resolutions, different image sizes, etc.

3 Related work

3.1 Fingerprint Verification Competitions at the University of Bologna

Since 2000, a fingerprint verification competition (FVC) has been organised at the University of Bologna every two years [FVC06]. Suppliers of fingerprint verification systems are asked to send in their feature extraction/comparison subsystems in the form of a Win32 console application. The performance of these subsystems is then tested offline against several finger image databases, one of which always contains synthetic fingerprint data. The interoperability of subsystems of different suppliers has not been examined in the FVC tests to date, though in FVC06, which commences later in 2006, it is planned to examine the accuracy of minutiae extraction.

3.2 BioFinger

The project BioFinger [BioFinger04], initiated by the German Federal Office for Information Security (BSI), had the task to evaluate different fingerprint recognition systems on the basis of achieved error rates (ROC curves). A test scenario for systems consisting of subsystems from different suppliers was also specified, but could not be put into practice due to general incompatibility of the subsystems of different suppliers. There was a lack of information about the data formats in use.

3.3 ILO seafarers' identity documents biometric interoperability testing

In 2004, the International Labour Organisation (ILO) commissioned a first performance and interoperability trial to evaluate minutiae-based products for use in a globally interoperable system of seafarers' identity documents. For the trial, the normal-size card format defined in the draft version of September 2003 of [ISO/IEC 19794-2] was to be used as a common data interchange format by all products under test.

In the first trial, the products of seven vendors have been tested for interoperability. Each vendor provided a fingerprint capture/minutiae extraction subsystem and a minutiae-comparison subsystem. The subsystems of the different vendors were tested in combination with each other using the subsystem from one vendor for minutiae generation at enrolment time and the subsystem from another vendor for both minutiae generation and comparison at verification time.

Fingerprints were captured online on the seven different fingerprint capture devices from a population of 126 seafarers during three visits per person. For each of the test subjects, two fingers, in general the left and the right index finger, were enrolled.

The ILO criterion of interoperability is an FRR of 1% or less at an FAR of 1% (i.e., an EER below 1%). The first trial showed clearly that interoperability problems can occur when using subsystems from different suppliers for enrolment and verification. The products of only two of the seven participating vendors satisfied the ILO criterion of interoperability [ILO04].

The vendors got the chance to update their software, and six vendors participated in a follow-on test commissioned by ILO. The follow-on test was carried out offline using finger images collected in the first trial. The follow-on test delivered better results than the first trial. Now, the products of three of the six participating vendors satisfied the ILO criterion of interoperability. Some of the interoperability problems among the products of the participating vendors had been resolved. Annex B of [ILO05] summarises what interoperability issues were encountered and how the vendors resolved them.

At the end of 2005, ILO has declared its intention to have a further round of conformance, performance, and interoperability testing for minutiae-based products to be used with seafarers' identity documents. This round of testing is underway, and results are anticipated by April/May 2006[2].

[2] June 2006 – The tests are now complete; publication of results is expected this Autumn

3.4 Minutiae interoperability exchange test MINEX

The minutiae interoperability exchange test MINEX has been performed by NIST [NISTIR 7296]. In addition to interoperability testing, MINEX aimed at testing the sufficiency of the minutiae format standardised in [ANSI/INCITS 378], i.e., at testing whether systems that use the standardised format for data interchange can achieve a recognition performance comparable with that of systems that use proprietary formats. MINEX tested systems that use the following data formats:

- Min:A, minutiae data format of [ANSI/INCITS 378], coding minutiae location, angle, type, and quality,
- Min:B, Min:A with additional ridge count, core and delta information (supported by six vendors only), and
- proprietary data formats (used only when the same vendor's software is used for enrolment and verification).

14 vendors submitted their software to participate in the test. The software delivered by the vendors contained mutually exchangeable minutiae extraction and comparison subsystems.

Four different finger image databases were used in the test, originating from the US Department of Homeland Security (DHS), the US Department of State (DOS), US Consular Offices, and from persons entering the USA at airport ports of entry (POE). In all cases, images from the left and the right index finger were collected.

The following interoperability test scenarios were performed:

- Scenario 1: Using software from one vendor X for minutiae extraction at enrolment time and software from another vendor Y for both minutiae extraction and comparison at verification time.
- Scenario 2: Using software of three different vendors X, Y, and Z for minutiae extraction at enrolment time, minutiae extraction at verification time, and comparison.
- Scenario 3: Using software from one vendor X for minutiae extraction at both enrolment and verification time and from another vendor Y for comparison.
- Scenario 4: The same as scenario 2, but using identical images for minutiae extraction at both enrolment and verification time.

MINEX did not apply a fixed criterion for interoperability, but looked at a variety of performance criteria, (e.g. false reject rates at various false accept rates, as well as false reject rates at various false accept rates) and methods for selecting interoperable sets of minutiae extraction and comparison algorithms.

It was shown that an EER of less than 1% is achievable with minutiae-based subsystems from different vendors, but it cannot be guaranteed by just prescribing the minutiae data interchange format.

A result of the data format sufficiency tests is the fact that the error rates achieved with proprietary data formats (that are not necessarily minutiae-based) may be significantly better than those achieved with the standardised minutiae data format. The error rates achieved with the standardised minutiae data format in homogeneous systems, however, were not

significantly better than those achieved in heterogeneous systems. This indicates that the minutiae data format standard is not sufficient to enable a recognition performance as high as that of proprietary non-minutiae solutions. The error rates achieved with enhanced minutiae data as per Min:B were only marginally better than those achieved with data as per Min:A.

MINEX does not lead to a repeatable certification process. Indeed, concerns were expressed by vendors and by the IBIA (International Biometrics Industry Association) when it was proposed that the MINEX results might be used to qualify products for use in the US PIV programme (a federal employee identification card initiative).

Factors for consideration in MIT:

- Typical single finger error rates for interoperable systems were (for 2 finger verification) FMR = 0.1%, FNMR = 1%. If the MIT project is seeking an improvement in interoperability, the performance requirement will need to be at this level or better.
- There are some operationally relevant scenarios that were not tested in MINEX. For example, when all recognition subsystems at any verification station are supplied by the same vendor, it would seem logical to allow comparison of a (proprietary) image-based record against the minutiae template, instead of requiring that the process is one of minutiae extraction followed by minutiae comparison.
- Testing the interoperability of 14 systems, MINEX is considered the largest performance test ever undertaken. The effort / cost / duration makes it impractical to re-run such tests on a frequent basis, with an ever increasing number of systems to certify an ever-increasing list of interoperable systems. Consideration within MIT of ways to reduce the overall size of these tests would be beneficial.
- The test reports the interoperable performance achieved, and does not certify future interoperability of these systems.
- The issue of selecting the best interoperating groups remains an open issue.
- The reported results are restricted to performance interoperability measures, though there was a 4-stage process of conformance test and algorithm modifications to ensure that the tested software was conformant and would operate to the MINEX protocols.

4 Issues for measuring / certifying interoperability

1. **Is a single performance threshold adequate as a threshold for assessing interoperability?**

   MINEX and the ILO seafarer's ID interoperability tests both assess interoperability as meeting a specified performance level. As a consequence certification of interoperability is nothing more than a certification of performance of a heterogeneous system (and we know that performance will depend on environment and population as much as it does on the minutiae extraction and comparison algorithms). We find that a minutiae extraction subsystem that does not meet the performance criteria when deployed at beth enrolment and verification time is deemed not to be interoperable with itself! It is desirable to have methods to assessing whether, for example, two minutiae extraction algorithms are sufficiently similar that

one may be substituted for the other with little impact on performance, in a manner where there is less dependency on factors such as environment and population.

One possibility may be to specify an error budget, splitting the error rates into components due to the underlying data (on which all systems fail), those due to extraction, those due to comparison, and those due to interoperability issues. This may help in certifying "substitutability" alongside consideration of overall error rates. Such models for sources of error are amenable to statistical analysis, and are to be investigated within MIT, to determine whether such an approach can helpful identify the factors which improve or which hinder interoperability.

2. **Size and speed of test**

   MINEX tested interoperability between 14 systems. This test is thought to be the largest performance test yet conducted of biometric systems, lasting several months and consuming significant number or person-months and computer processing cycles. Such a test duration can easily exceed the update cycle of the algorithm subsystems being tested, and if so, the results are immediately out-of-date. If this style of cross-system performance test (with large data set) is to be used to certify interoperability with earlier versions of algorithms, this would quickly multiply the number of algorithms to be tested consequently such testing is unlikely to get faster. Other methods for quickly evaluating that subsystems are likely to be interoperable are needed; the role of such cross-system performance tests might then become that of validating these other methods.

3. **Possibility of sets of interoperable implementations**

   Previous tests, both MINEX and the ILO tests, have shown that it is possible to have more than one set of implementations meeting interoperability criteria (with the union of these implementations failing the same criteria). This creates concerns about the incremental interoperability test process where it is desired to add further implementations to the interoperable set as time progresses: systems may be included or excluded depending on their position in the sequence of systems being tested.

4. **Performance outliers**

   When only testing performance interoperability between a few systems, there is less evidence to be able to attribute poor performance of combination to one of the subsystems.

5. **Any subset of an interoperable set of minutiae extraction and comparison algorithms should also be considered interoperable**

   For example, if minutiae extraction algorithms {A, B, C} are deemed interoperable with minutiae comparison algorithms {X, Y, Z} then {A, B} should also fulfil the criteria for being considered interoperable with {X, Y}. E.g. if the cross-system performance matrix under MINEX Scenario 1, is

FRR	A, X	B, Y	C, Z
A	0.5%	2.5%	1.0%
B	1.5%	0.5%	1.0%

C	0.5%	1.0%	0.5%

The set {A,B,C,X,Y,Z} has an average FRR of 1%, but the set {A,B,X,Y} has an average FRR of 1.25% The full set meets a performance requirement of average FRR ≤ 1%, while the subset does not.

6. **Certification of performance interoperability may require different processes from measurement of performance interoperability**

   For measurement of performance it is usual to give a best estimate, (and perhaps some statement of uncertainty). Actual performance may be worse or better than this estimate. Certification errs on the side of pessimism, so that even allowing for uncertainty in the performance measures, we are still statistically confident that the error rates are within the specified bounds. [E.g. to certify that an error rate is less than 3%, we might require an observed error rate of less than 1% in 100 trials.]

7. **No ground truth for minutiae locations**

   For issues such as minutiae placement, even fingerprint experts do not necessarily agree.

8. **Maintaining interoperability status**

   Depending on the method for determining the interoperability status of (groups of systems), the status may change as the number of systems increases or decreases.

5 Conformance testing with respect to [ISO/IEC 19794-2]

5.1 Motivation

In order to improve the chances of interoperability through standardization, the individual subsystems within a heterogeneous system must conform to the established standards. In this spirit, conformance to standards is a prerequisite, though not a guarantee, for interoperability.

Conformance testing is the process of checking that a test object satisfies the normative requirements of a particular standard.

The finger minutiae data interchange format standard [ISO/IEC 19794-2] specifies format requirements on (full and compact) minutiae records,

- syntactic requirements, characterizing the structure of conforming minutiae records, and
- semantic requirements, characterizing relations among fields in conforming minutiae records or between fields in conforming minutiae records and the underlying input finger image(s).

Furthermore,

- biometric subsystems that produce minutiae records are required to produce records that conform to [ISO/IEC 19794-2], and
- biometric subsystems that accept minutiae records are required to accept records that conform to [ISO/IEC 19794-2].

Thus, subject to different test objects, the following distinct, but related types of conformance testing with respect to [ISO/IEC 19794-2] can be identified:

- minutiae record conformance testing (see Section 5.2),
- conformance testing of subsystems producing minutiae records (see Section 5.3), and
- conformance testing of subsystems taking minutiae records as input (see Section 5.4).

Only subsystems that have passed the conformance test will be subject to interoperability testing.

5.2 Minutiae record conformance testing

5.2.1 Meaning of conformance

A minutiae record conforms to [ISO/IEC 19794-2] if it satisfies the syntactic and semantic requirements on a (full or compact) minutiae record that are specified within the normative clauses of [ISO/IEC 19794-2].

5.2.2 How to test

Testing an individual minutiae record for conformance to [ISO/IEC 19794-2] requires

- format and internal consistency checking for assessing whether the fields of the minutiae record have valid values and relate to each other as required in [ISO/IEC 19794-2] and
- contents checking for assessing whether the fields of the minutiae record relate to the underlying finger image(s) as required in [ISO/IEC 19794-2].

Format and internal consistency checking requires, for instance, testing whether the actual length of data fields is equal to the length indicated in the corresponding length fields. Format and internal consistency checking can be conducted by decoder software that parses the minutiae record and checks it against the conformance requirements.

Semantic requirements with respect to relations between fields of a minutiae record and the underlying finger images cannot be validated based on the given minutiae record alone. Their validation requires the underlying finger image(s) as input besides the minutiae record itself.

5.2.3 Requirements on minutiae record conformance test tool

Within the MIT project a test tool for testing the conformance of individual minutiae records to [ISO/IEC 19794-2] is being developed. The test tool shall

- take any minutiae record and a (set of) finger image(s) that underlie the minutiae record as input,
- check the format and internal consistency of the minutiae record, and
- graphically superimpose the scaled contents of the minutiae record onto the corresponding finger image(s) and onto a reference minutiae record to aid the person running the conformance test (the test operator) in contents checking.

Whether or not the fields of the minutiae record relate to the underlying finger image(s) as required in [ISO/IEC 19794-2] shall be assessed by inspection by the test operator. This

assessment may be hard to make, especially in case of low-quality input images. Automating the contents checking would require universally accepted reference implementations of minutiae extraction and comparison subsystems to automatically compare the minutiae record under test with the underlying finger image(s). As yet, no implementations are universally accepted as reference implementations, but they might be chosen as a result of the MIT project.

5.2.3.1 FBI Universal Latent Workstation as an example

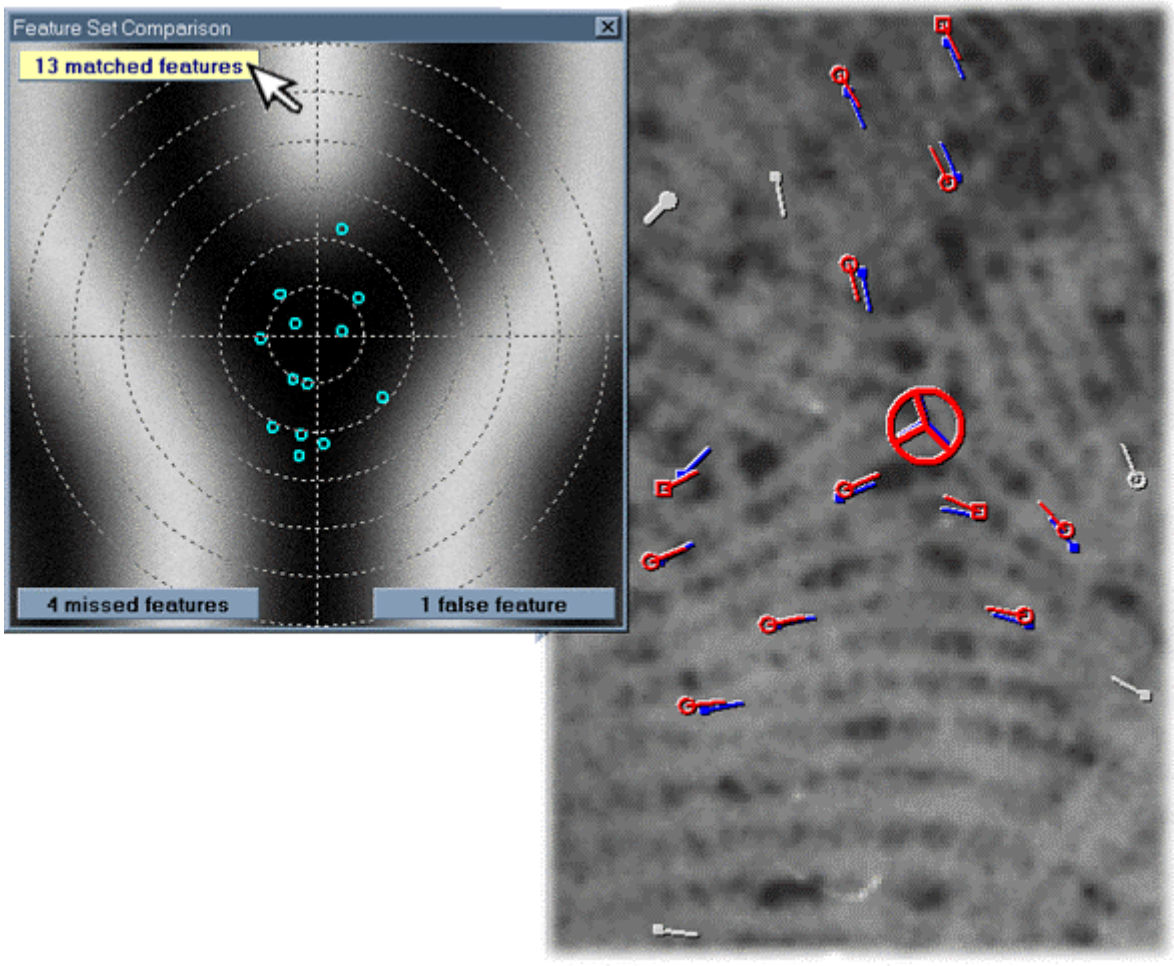

Figure 5. Example output of the FBI Universal Latent Workstation

The FBI Universal Latent Workstation software provides an example of what can be done in terms of a tool for comparison of minutiae extraction algorithm's minutiae placement etc. The tool is able to read in the minutiae records (in ANSI/NIST format) together with the source image used, and will (i) count the number of minutiae found by one algorithm but not the other, (ii) compare graphically, the minutiae placements overlaying the fingerprint image, and (iii) compare in schematic valley bifurcation, the offsets in minutiae placement. (it is also easy to see how this schematic could also be used to show difference in theta values (by adding tails to the dots in the diagram, and perhaps quality ranking (e.g. by using different intensities for the inner and outer rings of these dots).

5.3 Conformance testing of subsystems producing minutiae records

5.3.1 Meaning of conformance

A subsystem producing minutiae records conforms to [ISO/IEC 19794-2] if it satisfies the requirement that all minutiae records produced by this subsystem conform to [ISO/IEC 19794-2] in the way stated in the implementation conformance statement (see Section 5.3.2) associated with that subsystem.

Subsystems that may produce minutiae records are minutiae extraction and template production subsystems.

5.3.2 Implementation conformance statement

An implementation conformance statement (ICS) is a statement associated with each subsystem claimed to conform to [ISO/IEC 19794-2] and provided by the supplier of the subsystem, stating the supported

- options of [ISO/IEC 19794-2] and
- ranges of values for parameters of the formats specified in [ISO/IEC 19794-2].

ICS's are needed because not all subsystems claimed to conform to [ISO/IEC 19794-2] support all options of this standard (there may be, for instance, special-purpose subsystems that only support the compact-size card format but no other formats).

The ICS associated with a biometric subsystem will be used in

- selecting appropriate test data for the subsystem and
- forming sets of subsystems for which interoperability is possible.

In order that ICS's for different implementations are easily comparable, they shall follow an ICS template in the form of a questionnaire. The questionnaire queries which options and parameter values are supported by a given implementation. An ICS template for [ISO/IEC 19794-2] is included as Annex A.

5.3.3 How to test

A subsystem producing minutiae records can be tested for conformance to [ISO/IEC 19794-2] by

- processing all records from a finger image database and
- applying minutiae record conformance tests (cf. Section 5.2) to all the output minutiae records.

As exhaustive testing against all possible input images is impractical and also theoretically impossible, passing the conformance test cannot guarantee the conformance of the subsystem under test. However, passing the conformance test increases the confidence in a subsystem's ability to meet the requirements – based on the assumption that, if a subsystem works well in certain cases, it will work well also in other similar cases.

To inspire enough confidence to start interoperability testing, the finger image database used for conformance testing shall consist of at least 30 finger images (among them both representative and difficult finger images).

The finger image database for initial conformance testing within the MIT project need not be a sequestered database (which is available only to the test operators, but not to the developers of the subsystems under test). The finger image database for initial conformance testing may be distributed to the suppliers participating in the MIT project – who locate the minutiae (with their algorithms), and return the minutiae records.

In case of conformance testing for a formal certification, a sequestered database of 30 finger images will be used.

5.4 Conformance testing of subsystems taking minutiae records as input

5.4.1 Meaning of conformance

A subsystem taking minutiae records as input conforms to [ISO/IEC 19794-2] if it satisfies the requirement that it accepts every minutiae record that conforms to [ISO/IEC 19794-2] in the way stated in the ICS (cf. Section 5.3.2) associated with that subsystem.

An example of a subsystem that takes minutiae records as input is a comparison subsystem.

5.4.2 How to test

A minutiae comparison subsystem can be tested for conformance to [ISO/IEC 19794-2] by reading in and comparing all the records from a database of conforming minutiae records that are consistent with the associated ICS, a pair at a time.

Additionally we want to test some extreme values, not necessarily corresponding to a real fingerprint (e.g. 0 and 256 minutiae). There should be a set of tests, each looking at different aspects. For example, we might have some tests that examine whether a minutiae comparison subsystem can properly compare the same print scanned at different resolutions (here the minutiae coordinates will be different, since these are expressed in pixels rather than absolute measurements).

To inspire enough confidence to start interoperability testing, the minutiae database used for conformance testing shall contain minutiae records covering the full range of possible options. The minutiae database for conformance testing shall contain minutiae records produced by the minutiae extraction subsystems of all vendors participating in the MIT project and minutiae records that have not been generated in the MIT project (for example to have records representing a full range of resolutions, low and high minutiae counts). Such records might be synthesized using real fingerprint data, or might be entirely artificial.

The minutiae database for initial conformance testing within the MIT project need not be a sequestered database.

In case of conformance testing for a formal certification, a sequestered minutiae database will be used.

6 Performance interoperability testing

6.1 Cross-system performance tests

The draft standard ISO/IEC 19795-4 provides guidance on performance interoperability testing.

The approach is to conduct a technology evaluation measuring the performance of each cross-system combination on the same data sets. The process results in an interoperability performance matrix of performance results for each combination of extraction and comparison components. Both the MINEX and ILO tests are consistent with the draft.

6.1.1 Operationally relevant tests with representative data

The aim of such tests is to give data that is indicative of performance that would be achieved in the subsystem configurations of interest.

6.1.2 Performance tests with scenarios that are not operationally relevant, or restricted to difficult datasets

It can also be useful to consider cross-system performance tests in scenarios that are unlikely to occur in real life, or on data that is harder (or easier) than is typical for minutiae extraction or comparison. Such tests can be used to isolate interoperability issues. This may be particularly important to be able to test with smaller datasets for efficiency of the test process, (as well as due to the unavailability of large data sets).

For example, MINEX Scenario 4 has little operational relevance. In this scenario comparisons are made of a fingerprint against itself, but using two different extration algorithms in the process. Such tests may identify the fingerprint images where there are large discrepancies in minutiae extraction.

6.2 Interpretation of test results

The standard ISO/IEC 19795-4 is still in committee draft stage, pending development of guidance on how to interpret the performance interoperability matrix for the purposes of certification or selection of the best interoperating systems. Indeed, MIT project members are already contributing to this work.

The simplest approach is to compare the measured error rates within the interoperability matrix against specified performance requirements.

6.2.1 Simple example – comparison against performance requirement

Suppose the performance criterion is FRR ≤ 1% at an FAR of 1%, and the interoperability matrix, with minutiae extraction algorithms A, B, and C, and minutiae comparison algorithms X, Y and Z is

FRR at FAR=1%	A, X	B, Y	C, Z
A	0.5%	2.5%	1.0%
B	1.5%	0.5%	1.0%
C	0.5%	1.0%	0.5%

As previously discussed, while using the average error rate may be appropriate for measuring the level of interoperability between a given set of subsystems, it should not be used when it comes to certification. For certification it is important that any subset of subsystems certified as interoperable are also interoperable.

A set of algorithms can only be considered interoperable, if all values in the performance matrix are below a chosen limit. This way, the problem of subsets of interoperable subsets becomes superfluous.

The following subsets of components meet the interoperability criterion.

{A, C, X}: The minutiae extraction subsystems A and C are interoperable with respect to comparison subsystem X;

{B, C, Y}: The minutiae extraction subsystems B and C are interoperable with respect to comparison subsystem Y;

{A, B, C, Z}: The minutiae extraction subsystems A, B, and C are interoperable with respect to comparison subsystem Z.

If we want to find maximum interoperable subsets, including more than one comparison subsystem, e.g. X and Y, then we have to consider the intersection of the minutiae extraction subsystems interoperable with each of these comparison subsystems:

{C, X, Y, Z},

{A, C, X, Z},

{B, C, Y, Z}.

6.2.2 Statistical analysis

The approach of the simple example in 6.2.1 is one of measurement rather than certification. It informs on performance levels achieved, but provides no indication or guarantee that if the tests were repeated with different data (or parameters) similar interoperability results would be achieved. The MINEX and ILO tests demonstrate that the random nature of errors, changes in the database used, comparison alongside different sets of systems, or among greater number of systems can alter which systems are considered to be interoperable.

To overcome such issues, measures of performance interoperability are likely to require statistical analysis, perhaps attributing different portions of the error rates to the underlying images, to minutiae extraction, to comparison, and to different degrees of interoperability between components.

7 Conclusions

The following table summarises the agreed criteria for interoperability testing in MIT. The status indicates items agreed, items that will decided as the tests commence, and those items which are subject to investigation during the first phase of testing, and are likely to be modified or further instantiated for the second “certification phase” of the tests.

Item	Decision/Criterion/Target	Status
Components tested	Minutiae extraction Minutiae-minutiae comparison Minutiae-image comparison	Agreed

Minutiae format	ISO/IEC 19794-2: minutiae record format (single finger) compact card format (single finger)	Sub-options to be considered in lead up to testing. Formats must be supported by all suppliers
Fingerprint image format	ANSI/NIST	Agreed
Applications	Verification 1-finger Verification 2-fingers (vendor fusion of results)	Agreed
Scenarios	Minutiae-minutiae All combinations of 2 extraction algorithms, and 1 comparison algorithm (includes case where extraction of recognition image is combined with comparison algorithm from same vendor) Minutiae-image	Agreed
Target error rate for interoperability certification	2-fingerprint verification performance FRR < 0.5% at FAR <0.01% These error rates represent an improvement on the interoperable performance achieved in MINEX	Likely to be revised following investigative phase of tests
Thresholds (fixed/source variable) pre-set/post-test calibration	Allow source variable for investigative phase. Consider fixed & pre-set for certification phase	Investigate effects during first phase of test.
Types of test	Conformance Performance interoperability	Agreed
Interpretation of interoperability performance matrix		Investigate during phase 1
Investigations	Affect of quality (NFIQ) on interoperability Select datasets for conformance testing on the basis of performance results.	

References

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Annex A
Implementation conformance statement (ICS) template with respect to [ISO/IEC 19794-2]

A.1 Guidance for completing the template

A.1.1 Purpose

The purpose of this ICS template is to provide a mechanism whereby a supplier of a subsystem that is claimed

- to produce minutiae records conforming to [ISO/IEC 19794-2] or
- to take minutiae records conforming to [ISO/IEC 19794-2] as input

may provide, in a standardised manner, information about the

- options of [ISO/IEC 19794-2] and
- ranges of values for parameters specified in [ISO/IEC 19794-2]

that the subsystem supports.

A.1.2 Abbreviations and conventions

The ICS template comprises tables with the following columns:

- Item number: a number that identifies a row in the table
- Item description: description of an item in free text. Each row implicitly means “Is <item description> supported by the implementation?”
- Reference: refers to the relevant clauses of [ISO/IEC 19794-2]
- Status: statement of requirement of an item. The following notations are used:

M for mandatory (The feature is required to be supported.)

O for optional (The feature may be supported or not. If it is supported, then it shall conform to [ISO/IEC 19794-2].)

N/A for not applicable (In the given context, no requirement can be expressed.)

O.i for qualified optional (for mutually exclusive or selectable options from a set. <i> is an integer that identifies a group of related optional items. The requirement for their selection is defined immediately following the table.)

Ci for conditional (The requirement of the item depends on the support of other items. <i> is an integer identifying a conditional expression defined immediately following the table. The conditional expressions contain references to entries in the support column in the following form: <table identifier>/<item number>.)

- Support: response by the supplier of the implementation. The following notations are used:

Y for features supported by the implementation

N for features not supported by the implementation

N/A no answer (allowed only if status is N/A, directly or after evaluation of a condition)

- Values allowed: the values or the ranges of values allowed
- Values supported: the values or the ranges of values supported by the implementation

A.1.3 Instructions for completing the ICS template

The supplier of a subsystem that is claimed

- to produce minutiae records conforming to [ISO/IEC 19794-2] or
- to take minutiae records conforming to [ISO/IEC 19794-2] as input

shall complete a copy of this ICS template. If necessary, the supplier may provide additional information separately.

A.2 Identification of the supplier and the implementation

Table A.1 Identification of the supplier and the implementation

Supplier	
Contact point for queries about the ICS	
Implementation name	
Implementation version	
Other information necessary for full identification	
Have any exception items been required? (The answer "Yes" means that the implementation does not conform to [ISO/IEC 19794-2].)	
Date of statement	

Table A.2 Role of implementation

Item no.	Item description	Reference	Status	Support
1	Export of minutiae records		O.1	
2	Import of minutiae records		O.1	

O.1 At least one of these options shall be supported.

A.3 Supported formats

A.3.1 Major options

Table A.3 Major format options

Item no.	Item description	Reference	Status	Support
1	Record format	7	O.1	
2	Card format	8	O.1	

O.1 At least one of these options shall be supported. For a particular minutiae record, exactly one of these options shall be applied.

A.3.2 Options and parameters for the record format

The tables in this section need not be completed if the record format is not supported.

Table A.4 Parameter for the record format

Prerequisite: Table A.3/1

Item no.	Item description	Reference	Status	Values	
				allowed	supported
1	Number of finger views	7.3.10	M	0–176 (up to 16 views for 10 + 1 fingers)	

Table A.5 Optional extended data

Item no.	Item description	Reference	Status	Support
1	Ridge count data	7.5.2, 8.4.1	O	
2	Core data	7.5.3, 8.4.1	O	
3	Delta data	7.5.3, 8.4.1	O	
4	Zonal quality data	7.5.4, 8.4.1	O	
5	Vendor-defined extended data	7.5, 8.4.1	O	

Table A.6 Ridge count extraction method

Prerequisite: Table A.5/1

Item no.	Item description	Reference	Status	Support
1	Non-specific ridge count extraction method	7.5.2.1	O.1	
2	Four-neighbour ridge count extraction method	7.5.2.1	O.1	
3	Eight-neighbour ridge count extraction method	7.5.2.1	O.1	

O.1 At least one of these options shall be supported. For a particular minutiae record, exactly one of these options shall be applied.

A.3.3 Options for the card formats

The tables in this section need not be completed if the card formats are not supported.

Table A.7 Record size

Prerequisite: Table A.3/2

Item no.	Item description	Reference	Status	Support
1	Normal size finger minutiae format	8.1	O.1	
2	Compact size finger minutiae format	8.2	O.1	

O.1 At least one of these options shall be supported. For a particular minutiae record, exactly one of these options shall be applied.

Table A.8 Minutiae placement

Prerequisite: Table A.3/2

Item no.	Item description	Reference	Status	Support
1	Minutiae placement at valley-skeleton and ridge-skeleton bifurcation points	6.3.6	O.1	
2	Minutiae placement at ridge-skeleton end and bifurcation points	6.3.6	O.1	

O.1 At least one of these options shall be supported. For a particular minutiae record, exactly one of these options shall be applied.

Table A.9 Minutiae order

Prerequisite: Table A.3/2

Item no.	Item description	Reference	Status	Support
1	Minutiae not ordered	8.3.4	O.1	
2	Minutiae ordered by ascending x-y coordinates	8.3.4	O.1	
3	Minutiae ordered by descending x-y coordinates	8.3.4	O.1	
4	Minutiae ordered by ascending y-x coordinates	8.3.4	O.1	
5	Minutiae ordered by descending y-x coordinates	8.3.4	O.1	
6	Minutiae ordered by ascending angle	8.3.4	O.1	
7	Minutiae ordered by descending angle	8.3.4	O.1	
8	Minutiae ordered by ascending polar coordinates	8.3.4	O.1	
9	Minutiae ordered by descending polar coordinates	8.3.4	O.1	
10	Minutiae ordered by x or y coordinate extension	8.3.4	C1	

O.1 At least one of these options shall be supported. For a particular minutiae record, exactly one of these options shall be applied.

C1 if Table A.7/2 then O.1 else N/A

Table A.10 Optional extended data

Item no.	Item description	Reference	Status	Support
1	Ridge count data	7.5.2, 8.4.1	O	
2	Core data	7.5.3, 8.4.1	O	
3	Delta data	7.5.3, 8.4.1	O	
4	Zonal quality data	7.5.4, 8.4.1	O	
5	Vendor-defined extended data	7.5, 8.4.1	O	

Table A.11 Ridge count extraction method

Prerequisite: Table A.10/1

Item no.	Item description	Reference	Status	Support
1	Non-specific ridge count extraction method	7.5.2.1	O.1	
2	Four-neighbour ridge count extraction method	7.5.2.1	O.1	
3	Eight-neighbour ridge count extraction method	7.5.2.1	O.1	

O.1 At least one of these options shall be supported. For a particular minutiae record, exactly one of these options shall be applied.