

NIST Special Publication 500-336

Specification for Interoperability Testing of Contactless Fingerprint Acquisition Devices, v1.0

John Libert
Shahram Orandi
John Grantham
Bruce Bandini
Kenneth Ko
Christopher Stafford
Matthew Staymates
Craig Watson

This publication is available free of charge from:
<https://doi.org/10.6028/NIST.SP.500-336>

NIST Special Publication 500-336

Specification for Interoperability Testing of Contactless Fingerprint Acquisition Devices, v1.0

John Libert
Shahram Orandi
Bruce Bandini
Kenneth Ko
Craig Watson

*Information Access Division
Information Technology Laboratory*

Christopher Stafford
*Materials Science and Engineering Division
Material Measurement Laboratory*

Matthew Staymates
*Materials Measurement Science Division
Material Measurement Laboratory*

John Grantham
*Systems Plus, Inc.
Rockville, MD*

This publication is available free of charge from:
<https://doi.org/10.6028/NIST.SP.500-336>

June 2022



U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
Laurie E. Locascio, NIST Director and Under Secretary of Commerce for Standards and Technology

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

National Institute of Standards and Technology Special Publication 500-336
Natl. Inst. Stand. Technol. Spec. Publ. 500-336, 31 pages (June 2022)
CODEN: NSPUE2

This publication is available free of charge from:
<https://doi.org/10.6028/NIST.SP.500-336>

VERSION HISTORY

Date	Activity

Abstract

This guidance specifies a protocol and associated metrics for the evaluation of contactless fingerprint acquisition device, and their interoperability with legacy devices. This protocol enables contactless fingerprint developers seeking certification of their devices to perform an integral role in the collection of measurements by which their device will be evaluated by the certifying authority or other stakeholders. The NIST Fingerprint Registration and Comparison Tool (NFRaCT) enables interested parties seeking testing for certification to collect fingerprint images and performance measurements using NFRaCT and provides those measurements to the certifying authority for analysis and evaluation without requiring the exchange of any underlying fingerprint images. The protocol provides flexibility in that device performance can be evaluated and validated using live fingerprint impressions or three-dimensional (3D) fingerprint target artifacts.

Key words

Contactless fingerprint; image comparison; interoperability; registration; NFRaCT.

Table of Contents

1. Introduction.....	1
1.1. Overview	1
1.2. Rationale	1
2. How to use this document.....	2
3. Materials	2
4. Test Procedure	2
4.1. Image Acquisition	3
5. Assessment Criteria	3
5.1. Single Image Metrics	3
5.1.1. Image Entropy	3
5.1.2. Blind Signal to Noise Ratio (BSNR)	4
5.1.3. Image Contrast.....	4
5.1.4. NIST Fingerprint Image Quality (NFIQ) 2.....	5
5.2. Metrics Applied to Registered Mated Images	5
5.2.1. Computation of scale factor	5
5.2.2. Inverse RMS Difference of Spectral Image Validation Verification (SIVV) [12]Signals	6
5.2.3. Correlation of SIVV Signals.....	6
5.2.4. Structural Similarity Index	6
5.2.5. Correlation of Ridge Orientation Maps	7
5.2.6. Number of Corresponding Minutiae.....	7
5.2.7. Mean Displacement of Corresponding Minutiae	8
5.2.8. Free Pair Offset (Euclidean distance of the two unconstrained points used for registration)	8
5.3. Test Scoring	8
6. Conclusion	8
7. Acknowledgements	9
8. References.....	10
9. Appendix A: Test Artifact Examples	12
10. Appendix B: NIST Fingerprint Registration and Comparison Tool (NFRaCT)	14
10.1. Background	14
10.2. Obtaining NFRaCT	14
10.3. Image Requirements.....	14
10.4. Registering Images	15
10.5. Registration Results.....	20

List of Figures

Figure 1 - Geometric target patterns engraved in rigid polycarbonate material: Vertical Ronchi (left), horizontal Ronchi (center), and concentric circular (right)	12
Figure 2 - Engraved area of fingerprint target pictured in both rigid polycarbonate material (left) and flexible, flesh-toned PDMS (right).	12
Figure 3 - Fingerprint target cast in clear PDMS material (left) with flexible 3D-printed bone (right) embedded.....	13
Figure 4 - Format of RGP file contents	16
Figure 5 - Example RGP file contents (with Windows-style file paths)	16
Figure 6 – Fingerprint images displayed in NFRaCT.....	17
Figure 7 – Registration Candidates Legend.....	18
Figure 8 – Three pairs of corresponding registration candidate points added to each image.....	19
Figure 9 - NFRaCT toolbar icons on all three platforms, from top to bottom: Windows, MacOS, and Ubuntu Linux. Icons from left to right: Open, Save, Close, Add/Edit Comments, About. ...	19
Figure 10 - The NFRaCT Registration Preview window	20
Figure 11 - Example Registration Result Overlay with crop boundary at the max region of overlap (blue).....	21
Figure 12 - Sample XML output.....	23

Table 1 Abbreviations

ANSI	American National Standards Institute
BSNR	Blind Signal to Noise Ratio
CRADA	Cooperative Research And Development Agreement
DUT(s)	Device(s) Under Test – where “device” is a specific combination of hardware and software comprising an acquisition system
FIPS	Federal Information Processing Standard
FTIR	Frustrated Total Internal Reflection – optical principal employed by some fingerprint acquisition devices
GUI	Graphical User Interface
NFRaCT	NIST Fingerprint Registration and Comparison Tool (software)
NFRL	NIST Fingerprint Registration Library (software)
NIST	National Institute of Standards and Technology
PDMS	Polydimethylsiloxane
ppi	Pixels per inch (the customary unit of sampling for digital fingerprints)
ppmm	Pixels per millimeter
RMSD	Root-Mean-Squared Deviation (or Difference)
ROI	Region of Interest
SIVV	Spectral Image Validation Verification
TBD	to be determined

1. Introduction

1.1. Overview

Contactless acquisition of fingerprints presents a fundamental departure from legacy contact-based capture technologies. The friction ridge surface that comprises a fingerprint is a three-dimensional (3D) topography present on a three-dimensional pseudo-cylindrical surface of a finger. In all contactless devices examined to date, an image is first acquired in a format native to that device and then this image is processed to render a contact-compatible representation. The contact-compatible fingerprint impressions are two-dimensional (2D) representations of the three-dimensional structure presented by the finger being captured.

1.2. Rationale

Test procedures included in the Federal Bureau of Investigation (FBI)'s Electronic Biometric Transmission Specification (EBTS), Appendix F [1] and those for certification of devices for Personal Identity Verification (PIV) [2] evaluate interoperability by measuring specific attributes from images of test artifacts captured by each Device Under Test (DUT). Such attributes cover the gamut of geometric and optical properties indicative of image quality. Devices that have measured optical properties within limits prescribed by the specifications are deemed to be interoperable, the images generated by these devices to be acceptable, and certified as such. In general, this is true for contact acquisition devices that have passed the tests outlined in Appendix F and PIV. As noted in [3], devices using the same acquisition technology tend to produce images having greater interoperability than those yielded from devices of different technologies. Thus, images from FTIR devices tend to produce higher comparison scores against other FTIR devices than against Electro-Luminescence (EL) devices, etc. However, regardless of some variability among Appendix F certified devices, interoperability among them remains high, ensuring the integrity of contact or legacy fingerprint databases.

With the advent of contactless fingerprint acquisition, the interoperability landscape has changed. Because of the different means by which images of friction ridges are captured, the variations in capture geometry, and the processing applied to the initial photographic capture to create a legacy compatible representation, we were unable to identify Appendix F-like indicators and measures that are predictive of interoperability with contact imagery. Accordingly, we have adopted the approach of empirically testing interoperability via comparison of contactless images to contact exemplars. We do this both with fingerprint comparison algorithms and measurements of image features that relate to interoperability.

Thus, what is described in the sections to follow are some individual image measures that mainly assess the similarity of a pair of images relative to structure deemed relevant to comparisons – hence interoperability. In all cases, we compare images of fingerprints captured with a device under test to those same mated fingerprint images captured with a legacy contact device that serves as the exemplar.

2. How to use this document

This document defines a set of tests (measurements) and tools that can be used to obtain measurements for the testing, calibration and/or certification of a candidate fingerprint capture device (DUT).

While this document specifies what to measure and how, it does not define interpretation of those measures, nor does it define a certification or calibration regime. This document is meant to be referenced by domain specific certification/calibration guidelines (such as a guideline specific for law enforcement).

The measurements from the DUT will be compared to a reference measurement. The reference measurement can be obtained from specified standardized reference test phantoms/targets or reference measurements can be obtained from the test operator using another device already in compliance/certified.

Stakeholders seeking to establish a certification process will reference this document and will define specific interpretations of the measures described here.

It should also be noted that this document's scope is limited to the DUT, and not the Implementation Under Test (IUT), the latter of which can include other system components beyond the fingerprint capture apparatus.

3. Materials

Interoperability testing can be performed using either the test operator's fingers as a live target at the time of testing or can use specially fabricated standard reference test fingers artifacts from NIST.

The certifying authority or agency (such as the FBI, for example) referencing this document will specify allowable test apparatus (live fingers, or artifacts) necessary for their certification of a DUT, and the number of samples to be acquired from each.

4. Test Procedure

A certifying authority or agency will specify what procedures described in this special publication are necessary to allow for their certification of a DUT.

The test procedure described here involves capturing a fingerprint impression using the DUT, and another impression from the same finger using a reference device. A list of allowable reference devices is specified by the certifying authority.

The two images (DUT and reference) are then loaded into the software needed to conduct this test (NFRaCT) and the software will conduct a set of comparative tests on the image pairs.

The test software (NFRaCT) will then generate a score card.

This score card can then be provided back to the certifying authority to formulate their decision in issuing their certification for the DUT.

The number and position of fingers to examine from the DUT will be dictated by each respective certifying authority. For example, certain certifying authorities may require testing only index fingers for certification of a given DUT. Each finger position tested will generate its own score card.

Furthermore, the certifying authority will specify the impression type(s) required for the DUT (for example, only rolled equivalent, only FAP10[22], only plain, etc.) Each impression type tested will generate its own score card.

4.1. Image Acquisition

Image acquisitions will be performed by each respective device's native interface or software (DUT and reference device).

NFRaCT will only analyze these images and is unable to initiate capture for these devices.

Allowable special device settings (such as auto-capture, liveness detection, etc.) will be specified by the certifying authority or agency.

5. Assessment Criteria

Following the procedure described in [3] and in the following sections, the objective is to evaluate image attributes including structural fidelity of contactless fingerprints relative to contact exemplars. Some measurements are applied to individual samples independently and assessed in aggregate. Other measurements are applied to corresponding ROIs after registration and cropping of image pairs, with the image pair consisting of an image from the DUT and an image from the reference device.

5.1. Single Image Metrics

We apply a small number of measures to characterize features of both exemplar and query images irrespective of their correspondence.

5.1.1. Image Entropy

Entropy (E) [4] provides a measure of the extent to which the image utilizes the available range of grayscale values. Existing specifications such as [1][2] require pixel values to represent a dynamic range of 150 gray levels. We prefer to describe utilization of the grayscale range using entropy. Intermediate to high entropy tends to be preferred by humans[5], though it may not be important for machine matching of fingerprint images.

Entropy is defined as

$$E_I = -\sum_{i=1}^n p(x_i) \log_2 p(x_i) \quad (1)$$

where n = number of gray levels in the image, i.e. 256; x_i = the value of the i^{th} gray level; $p(x_i)$ = the probability of occurrence of the i^{th} gray level in the image. Thus, for a single channel (8 bit) image having $p(x_i) = 1/256$ for every i , the maximum entropy is 8, or 8 bits. Accordingly, an image displaying a relatively flat (uniform) gray level histogram should yield an entropy very near the maximum value of 8 bits. An image having less uniform distribution of gray levels, such as an image displaying large areas homogeneous in gray level would be expected to yield a lower entropy measure. Incidentally, the 150 gray levels mentioned above would correspond to entropy of approximately 7.23 bits.

5.1.2. Blind Signal to Noise Ratio (BSNR)

Zhang and Blum [6] describe a method for estimating the signal-to-noise ratio of images subjected to some noise or other degrading process in the absence of an original, unprocessed image for comparison. Boulton [7] summarizes experiments applying the metric to images corrupted by noise, JPEG compression, and contrast variation. The method involves analysis of the histogram of the edge intensity image, $\|\nabla I\|$, i.e., the L2 norm of the gradient of image, I , at each pixel location.

Thus, the procedure begins with the computation

$$\|\nabla I_{ij}\| = \sqrt{(I_{ij} - I_{i(j+1)})^2 + (I_{ij} - I_{(i+1)j})^2}, \quad i = 1 \dots n; j = 1 \dots m \quad (2)$$

The metric, Q , based on the distribution (histogram) of image gradient values is taken as the proportion of pixels of $\|\nabla I\| > 2\mu$, i.e.

$$Q = P(\|\nabla I\| > 2\mu) \quad (3)$$

where

$$\mu = \frac{\sum_{i=1}^m \sum_{j=1}^n \|\nabla I_{i,j}\|}{n \cdot m} \quad (4)$$

The metric, QR , blind signal to noise ratio, is then given as

$$QR = 20 \log_{10} \frac{Q}{e^{-\pi}} \quad (5)$$

The value, $e^{-\pi}$, is the minimum value for a signal consisting of Gaussian distributed noise and is used in the calculation as a base level for the metric – namely as Q approaches the minimum value for a Gaussian signal, QR approaches zero.

In the present instance, the procedure is applied to each of the cropped regions, I'_A and I'_B , common to both fingerprint images under comparison. In interpreting BSNR, one should keep in mind that it favors sharp edges and high contrast.

5.1.3. Image Contrast

Michelson contrast [8] is computed as

$$Contrast_{Michelson} = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}}, \quad (6)$$

where I_{Max} and I_{Min} are the maximum and minimum gray level values within the ROI that includes only pixels sampled from within the perimeter of the friction ridge region, i.e., excluding background. The region of a fingerprint image to be measured is defined as a rectangular area sampled from within the friction ridge region so as to exclude background pixels.

5.1.4. NIST Fingerprint Image Quality (NFIQ) 2

NIST Fingerprint Image Quality (NFIQ), version 2, is open-source software that links image quality of optical and ink 500 PPI fingerprints to operational recognition performance. This allows quality values to be tightly defined and then numerically calibrated, which in turn allows for the standardization needed to support a worldwide deployment of fingerprint sensors with universally interpretable image qualities. NFIQ 2 quality features are formally standardized as part of [10] and the software serves as the reference implementation of the standard. The open-source software is available for download at [11]. Since NFIQ 2 was trained using contact collected images, it is not recommended for use as a quality measure for contactless imagery at the time of this writing until further testing and training has been performed on the algorithm. This algorithm does however provide utility as a metric in conjunction with others defined in this special publication, and can provide a valuable signal with respect to contactless imagery as they evolve and achieve parity with contact collected imagery.

5.1.5. Total Power of the NIST Spectral Validation Verification (SIVV) Metric

The development of the SIVV metric is described in [12]. The total power of this metric, computed as the sum of the SIVV signal power at each sampled frequency, provides a second measure of image contrast [13].

5.2. Metrics Applied to Registered Mated Images

Registered mated images are key to this protocol and metrics applied to them are described in this section. Creating registered mated images can be accomplished with NFRaCT, described in detail in Appendix B

5.2.1. Computation of scale factor

Given that the points selected from the image pair correspond, we compute a scale factor by comparing the distances between the point pairs on the two images. Hence, given that we have two images I_1 and I_2 , we can designate sampled points from I_1 as P_{1x1} , P_{1y1} , and P_{1x2} , P_{1y2} . Corresponding points sampled from I_2 are then P_{2x1} , P_{2y1} , and P_{2x2} , P_{2y2} . We calculate the distances between the sampled points as

$$\begin{aligned} d_1 &= \sqrt{(P_{1x_2} - P_{1x_1})^2 + (P_{1y_2} - P_{1y_1})^2} \\ d_2 &= \sqrt{(P_{2x_2} - P_{2x_1})^2 + (P_{2y_2} - P_{2y_1})^2} \end{aligned} \quad (7)$$

The scale factor, then, is simply the ratio between the two distances

$$SF = \frac{\min(d_1, d_2)}{\max(d_1, d_2)} \quad (8)$$

In cases where the sample rate of the fixed image is known, we might multiply the scale factor by the expected sample rate in order to approximate the sample rate of the moving image. If the sample rate of the fixed image is 500 ppi, we can determine the deviation from either the Appendix F tolerance of $500 \text{ ppi} \pm 5 \text{ ppi}$ or the PIV Specification, $500 \text{ ppi} \pm 10 \text{ ppi}$.

5.2.2. Inverse RMS Difference of Spectral Image Validation Verification (SIVV) [12] Signals

Either differences or ratios of SIVV signals can provide quantitative measures for the comparison of images. For the present study, we examine image differences between pairs of images, I'_A and I'_B , with respect to the Root Mean Squared Difference (RMSD) between their two SIVV signals, s_1 and s_2 , over the entire frequency range 0 - 0.5 cycles/pixel.

$$RMSD(s_1, s_2) = \sqrt{\frac{\sum_{i=1}^n (s_{1,i} - s_{2,i})^2}{n}} \quad (9)$$

where $n = |s_1| = |s_2|$ (i.e., the lengths of the signal vectors).

This value is then inverted, by subtracting from 1, such that higher inverted RMSD scores will correspond with greater similarity between the two images.

5.2.3. Correlation of SIVV Signals

The RMSD measures the total deviation of point-wise comparison of the SIVV signals. The Pearson product moment correlation coefficient measures the parallelism between the two signals irrespective of the magnitude of the difference between them. Accordingly, we compute the correlation coefficient between s_1 and s_2 as

$$r(s_1, s_2) = \frac{\sum_{i=1}^n (s_1 - \bar{s}_1)(s_2 - \bar{s}_2)}{\sqrt{\sum_{i=1}^n (s_1 - \bar{s}_1)^2} \sqrt{\sum_{i=1}^n (s_2 - \bar{s}_2)^2}} \quad (10)$$

where \bar{s}_1 and \bar{s}_2 are the arithmetic means of their respective SIVV signal vectors.

5.2.4. Structural Similarity Index

The Structural Similarity Index (SSIM) [15] compares a pair of registered images assessing the visual similarity in terms of luminance, contrast, and structure. The formulation is applied block-wise to corresponding ROIs and then pooled to yield a single figure of merit for similarity of the image pair.

The SSIM Index quality assessment index is based on the computation of three terms, namely the luminance term, the contrast term and the structural term. The overall index is a multiplicative combination of the three terms.

$$SSIM(x, y) = [l(x, y)]^\alpha [c(x, y)]^\beta [s(x, y)]^\gamma$$

where

$$\begin{aligned} l(x, y) &= \frac{2\mu_x\mu_y + C_1}{\mu_x^2 + \mu_y^2 + C_1}, \\ c(x, y) &= \frac{2\sigma_x\sigma_y + C_2}{\sigma_x^2 + \sigma_y^2 + C_2}, \\ s(x, y) &= \frac{\sigma_{xy} + C_3}{\sigma_x\sigma_y + C_3}, \end{aligned} \quad (11)$$

Where $\mu_x, \mu_y, \sigma_x, \sigma_y$, and σ_{xy} are local means, standard deviations, and cross-covariance for images x, y .

By default, regularization constants for the three components, luminance, contrast, and structure are

- $C1 = (0.01 * L)^2$, where L is the specified dynamic range value of 255;
- $C2 = (0.03 * L)^2$, where L is the specified dynamic range value of 255;
- $C3 = C2/2$.

The SSIM function uses these regularization constants to avoid instability for image regions where the local mean or standard deviation is close to zero. Therefore, small non-zero values should be used for these constants.

We set $\alpha = \beta = \gamma = 1.0$ This simplifies the formula to

$$SSIM(x, y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_3)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_3)} \quad (12)$$

The SSIM values are pooled by averaging, hence we have the Mean SSIM, or MSSIM.

5.2.5. Correlation of Ridge Orientation Maps

We compare via correlation the block-wise estimates of ridge orientation. We create an orientation map of ridge orientation for each of the two overlapping regions of the registered images, I'A and I'B. For this we apply the method described in [16] as modified by Kovesi for a MATLAB function[17]. The method estimates the local orientation of ridges within a 7 x 7-pixel block centered on each pixel of the image being processed. The output is a map of angles in radians corresponding to the size of the input image. Thus, applying the procedure to the cropped regions of overlap, I'A and I'B, we get orientation maps, OA and OB. We then simply compute the 2D correlation of the two orientation maps.

5.2.6. Number of Corresponding Minutiae

NFRaCT utilizes an open-source matcher, SourceAFIS [21], to identify minutiae points that correspond across the pair of images undergoing registration. The count of the entire set of corresponding minutiae identified by SourceAFIS for a particular pair of images is output as a metric, under the assumption that the number of minutiae points determined to correspond between

the image pair could be dependent upon quality of the two images as well as similarity across the area of each.

5.2.7. Mean Displacement of Corresponding Minutiae

The transform to be applied to register the image pair is applied as well to any corresponding minutiae identified by SourceAFIS. The Euclidian distance between each pair is computed and the distances are averaged for output as a metric.

5.2.8. Free Pair Offset (Euclidean distance of the two unconstrained points used for registration)

In NFRaCT registration of a pair of images is performed as a two-step process: First, the moving image is translated such that one set of control points is brought into coincidence with those of the fixed image. This pair of points is referred to as ‘constrained’ as the distance between these two points will always be zero. Then, the moving image is rotated such that the other pair of points are brought into closest proximity. This pair of points is referred to as ‘unconstrained’ or ‘free’ and the Euclidean distance of their offset is taken as this metric. When multiple registration attempts occur due to the selection of more than two pairs of registration candidate points, this metric will represent the offset between the free pair of points that yielded the registration transform which maximized the MSSIM metric value (i.e., the optimal registration result for a set of registration candidates).

5.3. Test Scoring

For each metric, the NFRaCT software will tabulate values and compute as metrics the means and standard deviations of the measures for the DUT versus the reference device used.

These measures will be packaged in a special tamper resistant digital envelop and provided to the testing body.

The testing body can then submit this digital envelope to the certifying authority for validation and acceptance.

6. Conclusion

This guidance describes procedures, apparatus and measures that can be used as a basis for a contactless scanner certification regime by stakeholders. The certification regime established by each stakeholder (namely, the intended recipient of contactless fingerprint transactions) can reference this guidance and provide specific requirements of their operational use case and criteria based on the metrics defined in this guidance. The certification regime may contain further specialization and tailoring given the specific requirements of each stakeholder.

All references from certification regimes will be strictly traceable to this guidance, and shall note version information for this document, as well as version information for the test artifacts, and software version of NFRaCT used in conjunction.

7. Acknowledgements

This special publication would not have been possible without time and assistance from the many people who helped make it a possibility and a success. We would like to thank R. Michael McCabe and Gregory P. Fiumara for their time, advice, and candor in reviewing the contents of this special publication, and providing many meaningful suggestions to help make this a better publication.

8. References

- [1] FBI/CJIS, “Electronic Biometric Transmission Specification (EBTS) Technical and Operational Update (TOU) 11”, Federal Bureau of Information Criminal Justice Information Systems, Clarksburg, WV, April 16, 2021, <https://www.fbibiospecs.cjis.gov/Document/Get?fileName=Master%20EBTS%20v11.0.pdf> . Retrieved 10/08/2021
- [2] Personal Identity Verification (PIV) Image Quality Specifications for Single Finger Capture Devices, FBI/CJIS Biometric Specifications, 10 July 2006, <https://www.fbibiospecs.cjis.gov/Document/Get?fileName=pivs-spec.pdf> . Retrieved 04/18/2019.
- [3] Libert J, Grantham J, Bandini B, Wood S, Garriss M, Ko K, Byers F, Watson C (2018) Guidance for Evaluating Contactless Fingerprint Acquisition Devices, NIST Special Publication 500–305, National Institute of Standards and Technology, Gaithersburg, MD. <https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.500-305.pdf> . Retrieved 01/29/2021.
- [4] Gonzalez, R. C. and R. E. Woods, Digital Image Processing. New Jersey, Prentice Hall, 2008.
- [5] Tsai, D. Y., Lee, Y., & Matsuyama, E. (2008). Information entropy measure for evaluation of image quality. *Journal of digital imaging*, 21(3), 338–347. <https://doi.org/10.1007/s10278-007-9044-5>. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3043833/pdf/10278_2007_Article_9044.pdf (Retrieved 01/11/2022)
- [6] Zhang, Z and R. S. Blum. “On estimating the quality of noisy images.” IEEE 1998. <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=678131> , Retrieved 01/29/2021.
- [7] Boulton, T. Beyond Image Quality: Failure Analysis from Similarity Surface Techniques. presentation to NIST Biometric Quality Workshop, Gaithersburg, MD, March 2006.
- [8] Kukkonen H, Rovamo J, Tiippana K, Näsänen R. Michelson contrast, RMS contrast and energy of various spatial stimuli at threshold. *Vision Res.* 1993 Jul;33(10):1431-6. doi: 10.1016/0042-6989(93)90049-3. PMID: 8333164.
- [9] Stücker M, Geil M, Kyeck S, Hoffman K, Röchling A, Memmel U, Altmeyer P. Interpapillary lines--the variable part of the human fingerprint. *J Forensic Sci.* 2001 Jul;46(4):857-61. PMID: 11451067.
- [10] ISO/IEC 29794-4:2017(E) Information technology — Biometric sample quality — Part 4: Fingerprint image data
- [11] NIST Fingerprint Image Quality (2.1), National Institute of Standards and Technology (NIST). Accessed: 08/17/2021. [Online]. Available: <https://github.com/usnistgov/NFIQ2#readme>
- [12] Libert, J., Grantham, J., Orandi, S. A 1D Spectral Image Validation/Verification Metric for Fingerprints, NIST Interagency Report 7599, August, 2009 http://ws680.nist.gov/publication/get_pdf.cfm?pub_id=903078, Retrieved 01/29/2021.
- [13] Nill, N. B. Contrast effect on imagery power spectra. *Applied Optics/* Vol. 18, No. 13, July 1979. https://www.osapublishing.org/view_article.cfm?gotourl=https%3A%2F%2Fwww%2Eosapublishing%2Eorg%2FDirectPDFAccess%2FB0B8FEE1%2D537B%2D4F06%2D8A0E6FA13FDC7C28%5F23157%2Fao%2D18%2D13%2D2147%2Epdf%3Fda%3D1%26id%3D23157%26seq%3D0%26mobile%3Dno&org=National%20Institute%20of%20Standards%20and%20Technology%20Research%20Library%20%2D%20NIST (Retrieved 01/10/2022)
- [14] Karl Pearson (20 June 1895) "Notes on regression and inheritance in the case of two parents," *Proceedings of the Royal Society of London*, 58: 240–242
- [15] Zhou, W., A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli. "Image Quality Assessment: From Error Visibility to Structural Similarity." *IEEE Transactions on Image Processing*. Vol. <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1284395>, Retrieved 01/29/2021.
- [16] Thai, Raymond, Fingerprint Image Enhancement and Minutiae Extraction, Student Report submitted in partial fulfillment of requirements for the Honours Programme of the School of Computer Science and Software Engineering, The University of Western Australia, 2003, <https://www.peterkovesi.com/studentprojects/raymondthai/RaymondThai.pdf> , (Retrieved 06/18/2018)

- [17] Peter Kovesi. MATLAB and Octave Functions for Computer Vision and Image Processing. Available from: <<http://www.peterkovesi.com/matlabfns/>>
- [18] Libert, J, Grantham, J, Bandini, B, Ko, K, Orandi, S, Watson, C, Interoperability Assessment 2019:Contactless-to-Contact Fingerprint Capture, NIST IR 8307, National Institute of Standards and Technology, Gaithersburg, MD, May 2020.
<https://nvlpubs.nist.gov/nistpubs/ir/2020/NIST.IR.8307.pdf> , Retrieved 1/29/2021.
- [19] Orandi, S, Libert, J, Grantham, J, Bandini, B, Ko, K, Watson, C, Evaluating the Operational Impact of Contactless Fingerprint Imagery on Matcher Performance, NIST IR 8307, National Institute of Standards and Technology, Gaithersburg, MD, September 2020.
<https://nvlpubs.nist.gov/nistpubs/ir/2020/NIST.IR.8315.pdf> . Retrieved 01/29/2021.
- [20] Lisa Gottesfeld Brown, A survey of image registration techniques (abstract), ACM Computing Surveys archive, volume 24, issue 4, December 1992), pages 325 – 376
- [21] Važan, R, SourceAFIS open source fingerprint matcher, <https://sourceafis.machinezoo.com>. Retrieved 02/14/2022.
- [22] Special Publication (NIST SP) - 500-290e3: “American National Standard for Information Systems — Data Format for the Interchange of Fingerprint, Facial & Other Biometric Information,ANSI/NIST-ITL 1-2011 NIST Special Publication 500-290 Edition 3. August 22, 2016.
<http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.500-290e3.pdf>

9. Appendix A: Test Artifact Examples



Figure 1 - Geometric target patterns engraved in rigid polycarbonate material: Vertical Ronchi (left), horizontal Ronchi (center), and concentric circular (right)



Figure 2 - Engraved area of fingerprint target pictured in both rigid polycarbonate material (left) and flexible, flesh-toned PDMS (right).



Figure 3 - Fingerprint target cast in clear PDMS material (left) with flexible 3D-printed bone (right) embedded

10. Appendix B: NIST Fingerprint Registration and Comparison Tool (NFRaCT)

10.1. Background

In order to streamline the process of comparing fingerprint images captured on contactless devices to their contact counterparts, NIST has developed a software fingerprint registration and comparison tool. The NIST Fingerprint Registration and Comparison Tool (NFRaCT) allows a user to load a pair of fingerprint images, find corresponding points in both images, register and crop the images, and finally compute a series of measurements on the registered images.

Registration is a fundamental task in image processing and is used to align two or more pictures taken of the same object, for example, at different times, from different sensors, or from different viewpoints [4]. In the context of fingerprint imagery, registration can be used to bring fingerprint images of the same finger captured on different sensors into alignment for direct comparison. Many comparative image metrics require the images under comparison to first be registered. However, documented methods for automated registration do not perform well with biomorphic images, such as images of the same fingerprint captured using different sensors.

To facilitate registration of dissimilar fingerprint images, such as in the case of comparing contact impressions to contactless impressions, NFRaCT implements a method by which human evaluators can generate corresponding features from both images to be used as “control points” in a semi-automated process. Users are then able to view and optionally save the results of the registration process along with computed values for a variety of image metrics.

10.2. Obtaining NFRaCT

Information on obtaining the NFRaCT distribution can be found by visiting the URL <https://www.nist.gov/itl/iad/image-group/fast-capture>

If the URL above is not available, you can alternately contact fastcap@nist.gov for further guidance.

10.3. Image Requirements

NFRaCT is intended for use with 8-bit grayscale lossless fingerprint imagery.

While NFRaCT supports a number of other image formats as well as lossy compression algorithms (see supported image formats are listed in Table 2), only lossless (compressed or uncompressed) 8-bit grayscale images shall be used for certification testing because at the time of this publication the impact of lossy compression (such as Wavelet Scalar Quantization (WSQ) [22]) on the certification tests is not known and has not been quantified.

At the time of this writing, NIST is conducting a comprehensive study of WSQ with respect to contactless and this section will be updated accordingly as those results emerge.

Table 2 - Supported image formats in NFRaCT

Recommended Image Formats	
PNG	Portable Network Graphics
PGM/PBM/PNM	Portable gray/bitmap
BMP	Bitmap
JP2	JPEG 2000 (recommended for 1000 PPI fingerprint imagery)
Other Supported Image Formats	
JPG/JPEG	Legacy JPEG
TIF/TIFF	Tagged Image File Format
WEBP	Web-based image format
WSQ	WSQ The Wavelet Scalar Quantization algorithm

10.4. Registering Images

The main window of the NFRaCT interface displays two images side-by-side for comparison: Image #1, on the left side, is always designated as the “moving” image and Image #2, on the right side, is always designated as the “fixed” image.

“Moving” and “fixed” are terms commonly used in the context of image registration to clarify which image will be aligned to the other. Registration is a directional process; only one image is manipulated to be brought into alignment with the other image, which is not manipulated at all. In other words, the “moving” image will be repositioned in order to be aligned with the “fixed” image, which will not be repositioned or changed in any way.

Image registration in NFRaCT includes only translation (a shift in the image’s horizontal and/or vertical position) and rotation about a selected control-point, chosen automatically during the registration process. There is no “rubber sheeting”, scaling or skewing of the image contents in order to “fit” the moving image to the fixed image as in some other (non-biometric) image registration applications.

Ad-hoc comparisons of any two supported image files can be performed by using “drag-and-drop” to load image files into NFRaCT. Alternatively, batch comparisons are supported in NFRaCT in order to enable users to register many pairs of images efficiently via the creation of plain text files bearing the file extension “.RGP”. These files can be created/edited manually

or via automated methods and contain, at a minimum, paths to files for each fingerprint image. Optionally, these files can contain up to five pairs of registration candidate points and can also be annotated with comments. These RGP files can then be loaded into NFRaCT, as either a single file or a group of files to be processed as a sequence or batch.

```
PATH_TO_IM1
PATH_TO_IM2
<comment>
Text of arbitrary length
</comment>
IM1_X1, IM1_Y1, IM2_X1, IM2_Y1
IM1_X2, IM1_Y2, IM2_X2, IM2_Y2
[ ... ]
```

Figure 4 - Format of RGP file contents

```
C:\NFRaCT\Images\Image_01.png
C:\NFRaCT\Images\Image_02.png
<comment>
Test Comment
</comment>
561, 508, 405, 360
435, 288, 247, 162
```

Figure 5 - Example RGP file contents (with Windows-style file paths)

Following the format specified in Figure 4, each image file path is specified on one line followed by an optional comment and up to five pairs of registration candidates each specified on one line. In the example shown in Figure 5, x- and y-coordinates for each registration candidate point from “Image_01” are listed before the corresponding candidate point for “Image_02”. Any deviation from the format or order of coordinates provided in RGP files may produce unexpected results.

One particular use-case of interest in automatically generating RGP files to be loaded in NFRaCT may be to provide registration candidates extracted by a third-party system, such as a commercial fingerprint matcher.

Upon loading fingerprint images, via either drag-and-drop or RGP files, the user will be presented with an interface that displays both images along with their corresponding control panels on the left and right sides of the interface as seen in Figure 6. These controls allow the user to adjust the view of each fingerprint image, similar to common image viewing software.

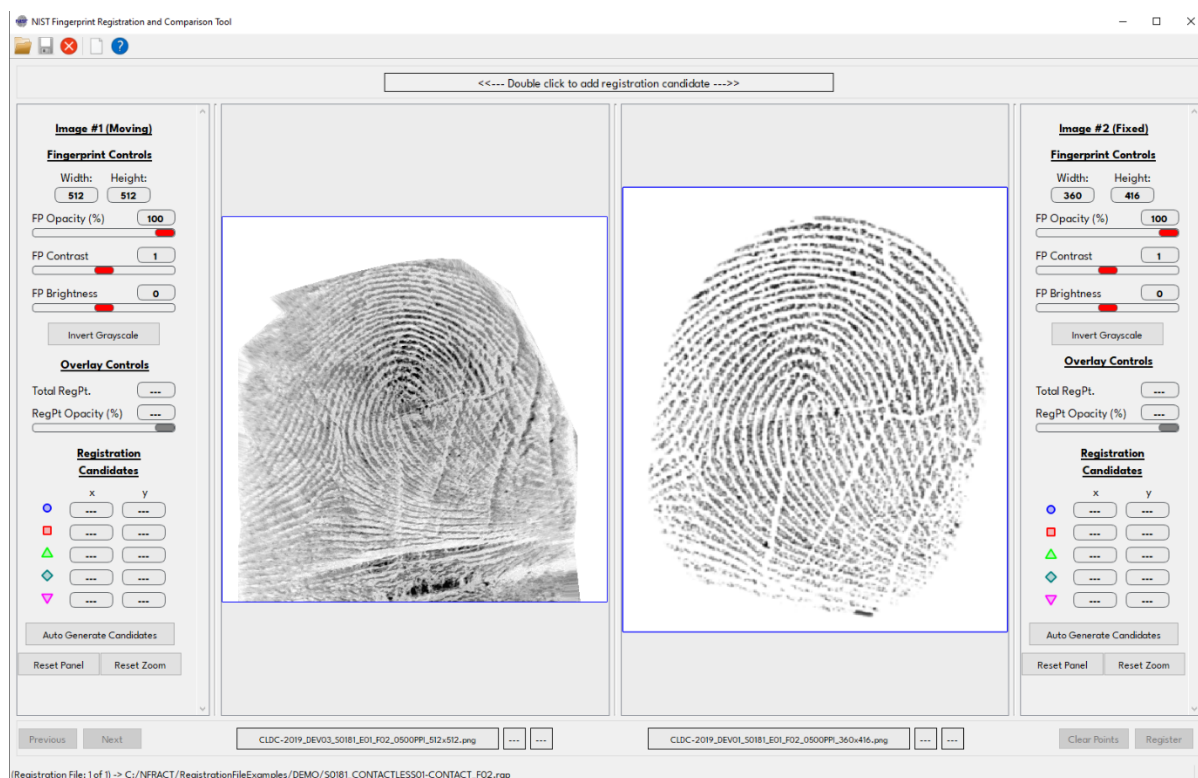


Figure 6 – Fingerprint images¹ displayed in NFRaCT

To begin the registration process, at least two pairs of corresponding registration candidate points must be provided. These candidate points do not necessarily have to represent fingerprint minutiae or features such as ridge endings or bifurcations but should represent what is believed to be corresponding salient features between the two fingerprint images (such as a scar, wrinkle, or burn).

For each test trial two impressions are required, one from the DUT and another from the reference device or reference target/artifact, as defined by the referring guidelines. Each pair will be designated by both a color and a shape unique to each pair when overlaid on images as shown in Figure 8.

¹ Images used for the demonstration of NFRaCT in this document were provided by a NIST volunteer staff member and used with permission.

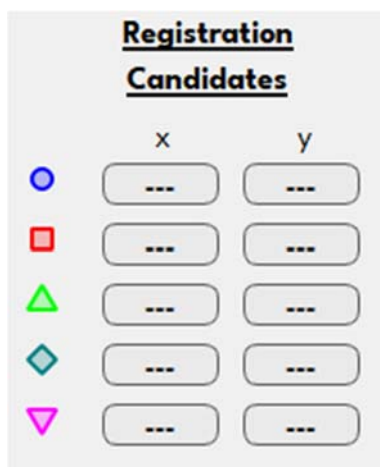


Figure 7 – Registration Candidates Legend

When more than two corresponding pairs are provided, NFRaCT will compute multiple registration attempts on all available pairs of selected features and establish the best (closest) matched pairing from the available set. Depending on the accuracy of the candidate points, providing more than two pairs to NFRaCT may increase the chances of achieving an optimal registration result based on the amount of overlap the registration algorithm can detect between the image pairs with an optimal registration being gauged as one where the two images produce the highest mean structural similarity (MSSIM) value after registration.

Registration candidate points can be manually selected by the user or automatically generated by NFRaCT using the open-source SourceAFIS matcher [21]. Users can initiate automatic generation of candidate points by clicking the “Auto Generate Candidates” button in the main NFRaCT UI (see Figure 6). NFRaCT will then select up to five pairs of registration candidate points from a set of corresponding points produced by the SourceAFIS matcher, using the moving image as a probe and the fixed image as the exemplar (also referred as “candidate” by SourceAFIS). If more than five pairs of corresponding points are produced by SourceAFIS, NFRaCT selects the five pairs which are most evenly distributed in terms of their positions across the two images.

Manually selecting and adding a registration candidate point to an image is performed by double-clicking on the location within an image where you would like to place a candidate point. When a new registration candidate point is added, NFRaCT will display a message guiding the user to add a corresponding point to the other image before continuing. Registration candidate points must be added as pairs, or one point for each image at a time. Three pairs of registration candidates are shown in Figure 8.



Figure 8 – Three pairs of corresponding registration candidate points added to each image¹

After selecting corresponding points, the user is able to modify the position of a candidate point by clicking and dragging the point to another location. A pair of points can be deleted by right-clicking on either point in a pair, and all points can be cleared from both images by clicking the “Clear Points” button in the lower-right of the interface.

Comments can be added to images registrations by clicking the add/edit comments icon in the toolbar, as shown in Figure 9. When saving, comments will be included in the RGP file. Registration candidate points can be saved to RGP files, along with comments, at any time by clicking the “Save” button in the toolbar, also shown in Figure 9.

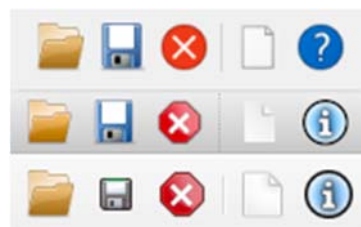


Figure 9 - NFRaCT toolbar icons on all three platforms, from top to bottom: Windows, MacOS, and Ubuntu Linux. Icons from left to right: Open, Save, Close, Add/Edit Comments, About.

Finally, once at least two pairs of registration candidate points have been selected, the “Registration” button in the lower-right of the interface can be clicked to perform the registration process.

10.5. Registration Results

NFRaCT will display the results of the registration process as seen in Figure 10 for review or further action by the user.

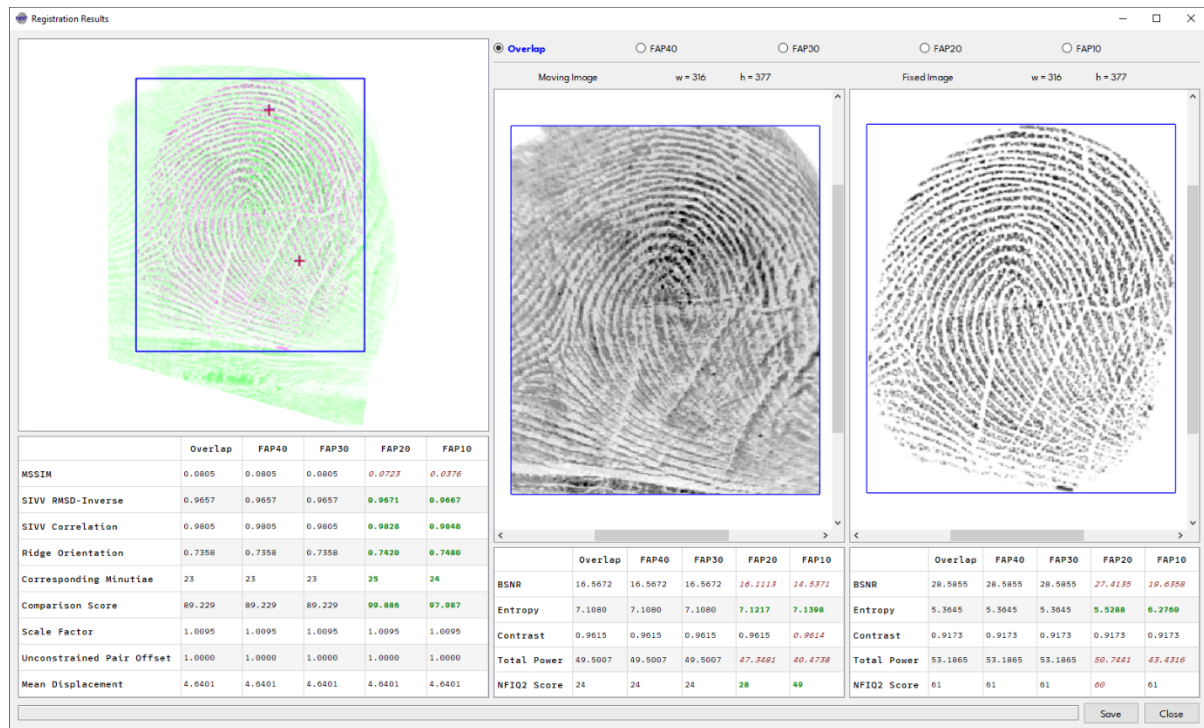


Figure 10 - The NFRaCT Registration Preview window

The registration results window shown in Figure 10 allows the user to see an overlay of the two registered images in the form of both the moving and fixed images appearing in contrasting green and purple colors, overlapping one another in order to visually depict the accuracy of the alignment between the two images. This visualization of the alignment can assist the operator in determining [subjectively] if the registration process had a significant failure, as well as where the greatest dissimilarities of the image agreement are located which could possibly allow for corrective action by the operator. Significant misalignment of the two images, potentially resulting from a poor registration, should be apparent when viewing the overlay as well as the individual registered images. Additionally, red and blue crosshairs are superimposed on the colored overlay image to show the two pairs of optimal registration points chosen by NFRaCT from the registration candidate points used to generate the registration result. This shows the registration point’s relative positions after registration. Due to the nature of the registration process, one pair of candidate points, the control points, will always be in perfect alignment, thus appearing as a single purple crosshair. Finally, a blue bounding box indicates the area of overlap between the two images, which also defines the crop area of each

image in the final registered images. If a user is not satisfied with the alignment or other aspects of the registration results, they have the option of closing the registration window and modifying or replacing registration candidates to potentially improve the registration results.



Figure 11 - Example Registration Result Overlay with crop boundary at the max region of overlap (blue)

A preview of the final registered and cropped images appears on the right side of the registration results window, along with five radio buttons that allow the user to see an overlay of various Fingerprint Acquisition Profiles (ie, FAP10, FAP20, FAP30, and FAP40) as defined in [22] depicted as bounding boxes, relative to the center of the cropped and registered images.

The registered and cropped images may be saved by clicking the “Save” button and choosing a location to save the results. If the user is not satisfied with the results of registration, clicking the “Cancel” button will return to the main interface where the user can modify or select new points and attempt registration again.

When saving, the results will include the cropped images at the size of the overlapping area between them as well as any FAPs which can be extracted from the overlapping images without additional padding, as well as an XML file containing only measurements computed from each supplied pair of images. To prevent tampering with the results, an encrypted version of the

XML will also be saved to a .ENC file which can be securely submitted to the certifying authority for review. Sample XML output is shown in Figure 12.

Once the “Save” button is clicked, the resulting registered and cropped images will be saved to disk in the location chosen by the user with the same filename as the RGP file associated with this registration. If the registered and cropped images are large enough to extract FAPs without padding, these images will be saved as well and labeled accordingly.

```
<?xml version="1.0" encoding="UTF-8"?>
<nfract>
  <metrics>
    <original_size>
      <moving_image>
        <bsnr>26.7147</bsnr>
        <entropy>6.98989</entropy>
        <contrast>0.939163</contrast>
      </moving_image>
      <fixed_image>
        <bsnr>20.1059</bsnr>
        <entropy>7.30098</entropy>
        <contrast>1</contrast>
      </fixed_image>
      <mssim>0.0719338</mssim>
      <scalefactor_moving_to_fixed>1.00084</scalefactor_moving_to_fixed>
      <scalefactor_delta>0.000841187</scalefactor_delta>
      <free_pair_offset>0</free_pair_offset>
      <ridge_orientation>
        <correlation_of_ridge_orientation>0.782453</correlation_of_ridge_orientation>
      </ridge_orientation>
      <moving_image>
        <mean_reliability>0.74396</mean_reliability>
        <reliability_standard_deviation>0.204771</reliability_standard_deviation>
      </moving_image>
      <fixed_image>
        <mean_reliability>0.729655</mean_reliability>
        <reliability_standard_deviation>0.194531</reliability_standard_deviation>
      </fixed_image>
    </metrics>
    <si_vv>
      <rmsd>0.0347889</rmsd>
      <moving_image>
        <total_power>90.3041</total_power>
      </moving_image>
      <fixed_image>
        <total_power>83.9709</total_power>
      </fixed_image>
    </si_vv>
  </original_size>
</metrics>
<nfract>
  <registration_metadata>
    <translation>
      <affine_transform>
        <rows>2</rows>
        <cols>3</cols>
        <row>1 0 -156</row>
        <row>0 1 -148</row>
      </affine_transform>
    </translation>
    <rotation>
      <affine_transform>
        <rows>2</rows>
        <cols>3</cols>
        <row>0.988260 0.152783 -155.441757</row>
        <row>-0.152783 0.988260 197.134613</row>
      </affine_transform>
      <angle>8.78822</angle>
      <center_of_rotation>1205, 1110</center_of_rotation>
    </rotation>
    <transform_points>
      <fixed_image>
        <constrained_point>1205, 1110</constrained_point>
        <unconstrained_point>1047, 912</unconstrained_point>
      </fixed_image>
      <moving_image>
        <constrained_point>1205, 1110</constrained_point>
        <unconstrained_point>1047, 912</unconstrained_point>
      </moving_image>
      <euclidean_distance>
        <constrained_point>0.000000</constrained_point>
        <unconstrained_point>0.000000</unconstrained_point>
      </euclidean_distance>
    </transform_points>
    <image_size>
      <src_moving>
        <wdth>800</wdth>
        <hght>750</hght>
      </src_moving>
      <src_fixed>
        <wdth>591</wdth>
        <hght>512</hght>
      </src_fixed>
      <transform_padded>
        <wdth>2191</wdth>
        <hght>2012</hght>
      </transform_padded>
      <registered>
        <wdth>587</wdth>
        <hght>457</hght>
      </registered>
    </image_size>
    <convert_gray>
      <src_moving>N0</src_moving>
      <src_fixed>N0</src_fixed>
    </convert_gray>
    <overlap_roi>
      <top_left>802, 803</top_left>
      <bottom_right>1389, 1260</bottom_right>
    </overlap_roi>
  </registration_metadata>
</nfract>
```

Figure 12 - Sample XML output