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Project FAP45: Examining the Impact of Fingerprint Image Stitching Errors on Search Performance

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Project FAP45: Examining the Impact of Fingerprint Image Stitching Errors on Search Performance

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Abstract

This study examines operationally related issues for slap-fingerprint submissions created by compositing (stitching) smaller images together. In an operationally modelled setting, these stitched images resulted in diminished matching ability. It was determined that the predominant root cause of most failures was the inherent quality of the fingerprint images followed by improper positioning of the individual images prior to stitching.

Keywords

Fingerprints; biometrics; biometric matcher performance; biometric quality, fingerprint stitching.

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1. Introduction

The criminal justice community has relied on fingerprints as a cornerstone of personal identification for well over a century [1]. There are currently two prevalent modes of fingerprint collection employed in operations worldwide: plain fingerprint impressions (also known as flat) where fingerprint detail is captured by pressing the finger friction ridge pad down onto the capture device and then lifted, and rolled fingerprint capture where the finger is first placed down on either the left or right edge and then rolled to the other edge on the capture device capturing more of its surface area in the operation (see Figure 1).



Figure 1: Example of a Flat Fingerprint Impression (left) and Rolled Fingerprint Impression (right) of the Same Finger [14]

While rolled fingerprint impressions are the "gold standard" for identification [2] due to their ability to collect forensically valuable friction ridge data from the sides of the finger, plain fingerprint impressions have rapidly gained acceptance for civil identification case work as well as border control measures. This is due to plain impressions being less susceptible to distortions during capture [3], faster collection speed from capturing up to 4 fingers from a hand at a time[1] [4], and fewer sequencing errors due to the intrinsic adjacency of fingers on each hand [2]. Collection of multiple prints at the same time does however require a platen large enough to physically accommodate all the fingers to be collected simultaneously.

Biometric matching systems have evolved significantly, yielding measurable improvements in both accuracy and throughput [5]. However, the performance of these systems remains heavily dependent on the quality of the captured fingerprints [2]. The quality of collected fingerprints can vary significantly, especially when collected under non-ideal circumstances such as during roadside police stops using portable devices. This has driven improvements in collection devices, including advancements specifically targeting increased portability for field use. To guide these hardware improvements, the stakeholder community established standards for smaller form-factor devices [6].

[1] This is referred to as 4-4-2 capture where all fingerprints from a subject can be captured in 3 collections comprising of capturing the left four fingers on the hand, then the right four fingers, and finally the two thumbs placed next to each other captured together. Rolled collection however would require 10 captures for 10 fingers resulting in slower collection time.

Improving portability usually involves reducing the device weight and dimensions. Depending on the extent of reduction in the dimensions of the device, the reduction may also necessitate a smaller collection platen on the device. Large-platen devices such as legacy stationary fingerprint collection devices or Mobile ID FAP60 [6] compliant devices have a 3.2" wide platen allowing them to collect up to 4 fingers from the subject's hand at one time. As the platen is reduced in size the device may still be able to capture multiple fingers simultaneously. For example, small-platen Mobile ID FAP45 [6] devices have a 1.6" wide platen which allows them to collect up to 2 fingers from a subject's hand at one time.

In order to ensure backwards compatibility with legacy plain collection devices that capture 4 fingers at a time, the Federal Bureau of Investigation (FBI) was made aware of devices that were capturing 2 adjacent fingers at the same time and stitching (also known as compositing or collaging) two such collections from a hand to create a simulated 4 finger capture similar to that of a legacy, stationary, large-platen collection devices.

In partnership with the FBI, the National Institute of Standards and Technology (NIST) launched an investigation in January 2025 to study unusual performance issues for seemingly good submissions (based on preliminary visual inspection) to the FBI Next Generation Identification (NGI) system that were resulting in higher-than-expected error rates by the NGI system. This study examined a number of affected transactions in an effort to determine the root cause of the failures.

2. Background

The FBI utilizes a modern Automated Fingerprint Identification System (AFIS) with orchestration operations for inbound transactions based on several criteria, such as transaction type, prior to processing on the NGI matcher. The orchestration operations perform preliminary checks and validation of inbound transactions and are responsible for routing transactions to the appropriate subsystem or operational pathway in NGI. This includes the checking of finger sequence and validation of the submitted fingerprints prior to orchestration into the matcher.

Some of the checks performed by the system depend on assumptions about the anthropometrics of a human hand, such as locations of the fingers, placement of the finger pads and their angle of rotation as well as an estimation of the inherent quality of the images.

3. Study Objectives

This study seeks to examine a collection of fingerprint submissions to the FBI NGI system that originated from small-platen Mobile ID devices (namely FAP45 devices that can capture two fingers at the same time) and compare the matching performance to submissions that originated from large-platen Mobile ID devices, and perform a comparative analysis of the biometric matching error rates under various test scenarios.

Under normal operating conditions, the large-platen devices can capture up to 4 fingers at the same time, while the small-platen FAP45 devices can capture up to 2 fingers at a time. It is

assumed that devices were used to capture the maximum allowable number of fingers for that given device respectively and no fewer.

4. Hypothesis

It is hypothesized that stitching may introduce errors which could impact matching performance. In order to explore this hypothesis, an intra-record examination is proposed to enable validation of this hypothesis by looking at records that contain both rolled as well as stitched images. Intra-record examination also has the advantage of minimizing longitudinal drift because all fingerprints are assumed to have been captured during the same session.

5. Materials

The FBI provided NIST with 54,069 sanitized biometric records in the Electronic Biometric Transmission Specification (EBTS) format [10] that had been submitted to the FBI from Mobile ID devices with mixed platform sizes. The FBI also supplied NIST with 26,155 unique reference database records (from the FBI Criminal Master File, or CMF) containing the matching exemplars to the Mobile ID submissions. The reference database records contain a full set of rolled (10) and flat impressions (4), analogous to the FD-249 fingerprint collection card [13] (See Figure 2). Initial examination of the Mobile ID records supplied showed that these records may not have been collected with the same requirements as the reference database records that are typically collected at a formal booking station. For example, some of the Mobile ID records contained only plain impressions and were not required to submit rolled impressions due to specific requirements of that specific transaction.

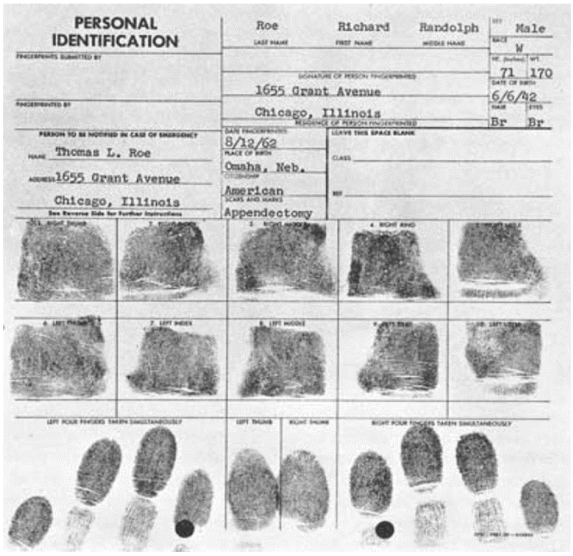


Figure 2 - Example of a Full Set of Fingerprints Collected at a Formal Booking Station [13]

6. Data Selection

To embark on this investigation, we opted for an ablation study (also known as pruning sensitivity analysis) to explore the effects of portions of data with other portions pruned or removed. The goal of this analysis strategy is measuring the difference that certain parts of the data have on system performance.

We began by analyzing the Mobile ID submission images utilizing automated tools to establish their completeness and composition. Automated analysis rejected 1,323 because they had no acquisition profile marking. A further 2,171 were rejected from analysis as they exhibited missing fingers/amputations that could skew our pruning sensitivity due to ablation of data not within the scope of the study. This yielded 51,898 records usable for this investigation (Table 1).

Finally, we performed an analysis of the transaction types. There was a total of five unique transaction types in the records provided by the FBI (TPRS: Ten print rap sheet search, FNDR: Federal No Charge Direct Route, DEU: Unknown Deceased, FANC: Federal Applicant-No Charge and CAR: Criminal Ten-print Submission-Answer Required). On examining some of these transactions, the team observed capture anomalies that may be attributed to poor operator training or conditions. On further deliberations with the FBI, the investigation team determined that we would limit the analysis to **only CAR transactions**. The reasoning for this was that anecdotal evidence shows that criminal submissions to the FBI (CAR transactions) are typically performed by law enforcement personnel with more stringent requirements on collection; the personnel undergo more formalized training on the collection of fingerprints [7] and perform collections in a well-controlled environment such as a dedicated police booking environment. This contrasts with DEU transactions, for example, involving fingerprint collection from a deceased individual by medically trained professionals in the field using personnel that may not have direct training in law enforcement. This further reduced the number of records used in the analysis as shown in Table 1 below.

Table 1- Composition of Submitted Data Set

SUPPORTED ACQUISITION PROFILE	MODEL	MAXIMUM FINGER CAPTURE	ALL RECORDS	CAR ONLY RECORDS
FAP50	Variant 1	4	16,952	3341
FAP60	Variant 1	4	329	0
FAP45	Variant 1	2	57	57
FAP45	Variant 2	2	4,889	1359
FAP45	Variant 3	2	29,671	8439
TOTAL			51,898	13,196

Next, all CAR Mobile ID data and the FBI reference database data underwent pruning to result in the data cases outlined in Table 2 to support our pruning analysis.

Table 2- Data cases for ablation study

TREATMENT	DESCRIPTION
Case 1	FBI CMF records with no changes (baseline)
Case 2	Mobile ID submissions, with no changes (baseline)
Case 3	FBI CMF records, rolled impressions only (plain impressions pruned)
Case 4	FBI CMF records, plain impressions only (rolled impressions pruned)
Case 5	Mobile ID submissions, rolled impressions only (plain impressions pruned) This treatment **cannot** contain stitched images (individual images only)
Case 6	Mobile ID submissions, plain impressions only (rolled impressions pruned) This treatment **may** contain stitched images

Next, a fractional factorial experimental matrix for the matching operations was established (Table 3) to guide the orchestration team in configuring the experiment on the NIST NGI Testbed (NNGITB), a friction ridge matching system modeled after the NGI system in use by the FBI. To model the reference database's conditions closer to that of the FBI CMF where the system operates with a sizeable reference database, an additional ten million biometric records were included in the reference database in addition to the data case of interest. While not all test cases in the fractional factorial matrix are immediately relevant to the goals of this experiment, they were run for completeness in the event that they could uncover additional insight.

Table 3- Test Cases

		Probe Sets					
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Reference database	Case 1 + 10mil	Test 1-1	Test 1-2	Test 1-3	Test1-4	Test 1-5	Test 1-6
	Case 2 + 10mil	Test 2-1	Test 2-2	Test 2-3	Test2-4	Test 2-5	Test 2-6
	Case 3 + 10mil	Test 3-1	Test 3-2	Test 3-3	Test3-4	Test 3-5	Test 3-6
	Case 4 + 10mil	Test 4-1	Test 4-2	Test 4-3	Test4-4	Test 4-5	Test 4-6
	Case 5 + 10mil	Test 5-1	Test 5-2	Test 5-3	Test5-4	Test 5-5	Test 5-6
	Case 6 + 10mil	Test 6-1	Test 6-2	Test 6-3	Test6-4	Test 6-5	Test 6-6

In examining issues with specific fingerprint images (as needed), subsets we examined using the Universal Latent Workstation (ULW) tool [11] and potential issues were coded and noted in a log.

6.1. Matcher

While the NNGITB shares many components with the NGI operational environment, it lacks the orchestration components needed to process transactions in an operational environment. Instead of the orchestration components, the NNGITB is equipped with special software tools that allow for the rapid querying of the matcher reference database with a provided probe.

The NNGITB supports two operational modes: The first is optimized for ten-print caseloads, and the other is optimized for Mobile ID caseloads. The configuration used for this investigation was the Mobile ID optimized configuration.

6.2. Scoring Methodology

The test cases in this investigation were executed as a closed-set 1:N (1 to N, also known as one to many) search scenarios where all probes are known to have a mate in the reference database. In comparing test cases, an approach for measuring absolute AFIS search performance in terms of match and non-match rates was tailored to provide a means of enabling a differential analysis (rather than absolute) for search scenarios in this investigation.

Mated searches are defined as searches of probes of subjects that are known to be enrolled in the reference database and thus expected to be returned in candidate lists. In the case of expected mates not being returned as the rank (R) 1, or top candidate, or as the top candidate but having a similarity score (S) below the system lights-out matching threshold (T) in the returned candidate list, these are considered to be false negatives and are used in calculating the False Negative Identification Rate (FNIR) for our differential analysis. FNIR here is defined as the ratio of the total number of mated search trials (N_M) where either the expected mate (EM) is not returned as the top candidate, or the top candidate's similarity score is less than the system lights-out threshold:

$$FNIR(T) = \frac{1}{N_M}\sum_{i=1}^{N_M}\begin{cases}1, if\ EM(R \neq 1) or\ S(R = 1) < T\\ 0, otherwise\end{cases}$$

In addition to the mated reference database records, the system also has 10 million additional records enrolled in the reference database. Any candidate returned at the top of the returned candidate list (rank 1) that is not the mated record is considered a false positive in gallery hit and is used to calculate the false positive in gallery hit rate (FPIG) in this investigation. If the candidate was indeed an actual match (confirmed through visual verification) to a previously unknown mate, it is treated as a consolidation true mate that has been discovered during the course of this investigation. Given N enrolled subjects, FPIG is defined as the number of trials where a mated person was searched, but the system returned a non-mate candidate (NM) with a score greater than or equal to T at rank 1 of the candidate list, over the total number of mated search trials conducted (N_M),

$$FPIG(T) = \frac{N_{NM}(R = 1, S \geq T)}{N_M}$$

6.3. Auto-Consolidations

The NNGITB reference database has been enrolled with 10 million additional (non-mated) records to model a system closer to the FBI production environment.

In cases where an unknown candidate is returned in the rank-1 position, the score of the candidate is examined. If the score is above a threshold of 20,000, it is treated as an auto-consolidation. The threshold of 20,000 was determined through previous tests conducted on the NNGITB where we have never encountered non-mates above this score.

7. Results

7.1. System Base Case

In this scenario (Test 1-2 from Table 3, no data filtering), we measured matcher performance across the mix of all Mobile ID submissions without restrictions on transaction or device type. Given the 51,898 submissions, the system exhibited a FNIR of 0.383% (n=199) and an FPIG of 0.106% (n=55).

7.2. Mobile ID submissions probes to FBI CMF reference database, CAR only.

In the first investigation scenario, Test 1-2 (see Table 3) is defined as the Base Case where the mobile ID transactions are matched against a reference database containing their exemplar mates. Other than selecting on the CAR-only subset of data (n=13196 transactions) no other filtering was performed on the data.

In this scenario (Test 1-2 from Table 3, CAR-only), the system yielded a measured FNIR of 0.371% (n=49) and an FPIG 0.076% (n=10).

7.3. Four-finger vs. Two-finger platen Mobile ID, CAR only, no other considerations

In the next investigation scenario (Test 1-2 from Table 3, CAR-only), we partition the Mobile ID submission data into small-platen collection (FAP45, n=9855, which can collect up to 2 fingers) and large-platen collection (FAP50, n=3341 which can collect up to 4 fingers). There were no CAR transactions at FAP60 so we will omit FAP60 for the remaining scope of this investigation.

In this scenario, FAP45 submissions (n=9855) yielded a measured FNIR of 0.355% (n=35) and FPIG of 0.061% (n=6). The FAP50 submissions (n=3341) yielded an FNIR of 0.419% (n=14) and an FPIG of 0.120% (n=4).

Table 4 – Search Accuracy by FAP

Submission Type	*n*	*FNIR*	*FPIG*
FAP45	9855	0.355% (n=35)	0.061% (n=6)
FAP50	3341	0.419% (n=14)	0.120% (n=4)

7.4. Intra-Record Integrity Baseline

A fully formed and properly collected CAR submission will contain ten rolled fingerprints, and corresponding plain images typically captured as slap images from each hand.

For the next steps in this investigation (Test 1-2 from Table 3, CAR-only), we looked at intra-record integrity check by fracturing a CAR submission into two discrete records the first of which consists of just the plain images, and the second composed of just the rolled images. We then independently match each of these two discrete transactions against a reference database which contains its exemplars.

Table 5- Search Accuracy by FAP and Impression Type

Collection	*FAP*	*N*	*FNIR*	*FPIG*
Plain	FAP45	9855	**0.731% (n=72)**	0.152% (n=15)
	FAP50	3341	0.988% (n=33)	0.239% (n=8)
Rolled	FAP45	9855	0.578% (n=57)	0.142% (n=14)
	FAP50	3341	0.898% (n=30)	0.120% (n=4)

7.5. Analysis of Error Cases

After quantitative analysis of the data, specifically on the performance of the FAP45 portion of the CAR transactions, further qualitative analysis was conducted on the error cases to gain additional insight into the potential root cause of the failures.

In order to conduct the qualitative analysis, we first performed inductive coding of the error data [15] to establish six coding categories that can describe all error cases encountered. The coded qualitative categories are listed in Table 6:

Table 6 – Qualitative Analysis Coding Table

QUALITATIVE ERROR CODING	DESCRIPTION	SUGGESTED MITIGATATION
Quality Issue	Anomalies that impact some or all of the fingerprints and include contrast, exposure, and haloing of the collected images.	Operator training on proper placement, position and speed/pacing the capture can help improve a portion of these observed issues.
Stitching Issue	Anomalies that are a direct result of stitching fingers to create a slap. These can include poor raster alignment of fingers (XY), and erroneous rotation of 1 to 3 of the fingers in the slap relative to the others up to 180 degrees.	Operator training on the correct placement (especially with respect to rotation of finger pairs and how portable scanners are held) that could mitigate most of these issues. Assistive placement devices on the collection device can also help mitigate these.
Capture Issue	Issues caused by poor capture technique including the finger slipping mid capture, collection of the wrong type of impressions and poor placement of fingers during capture.	Operator training may mitigate these issues.
Scanner Defect	Anomalies that include artifacts local to the device being used to capture fingerprints that systematically appear in two or more fingers.	Careful periodic inspection and examination of images from the device, and timely servicing or replacement can reduce the impact of this issue.
Reference database Poisoning	Cases where a stitched image appears to have been moved into the master reference database in a previous encounter through auto encounter quality updates.	Matcher orchestration can be modified to prevent ingestion of images from portable devices as replacements for existing reference database images.
Reference database Quality Issue	Cases where the database/exemplar images are of poor quality.	No mitigation recommendations within the scope of this investigation.

The sampling method for the qualitative examination used relied on the biometric matcher's responses to the search queries as described in section 6, pared down to those responses classified as false positive and false negative errors for the specific test cases of 1-5 and 1-6 as described in this section. Errors that both treatment cases had in common were not included and only those unique to each treatment were examined in the analysis (Table 7).

Each case examined may have been flagged for zero or more error categories. Each case was examined for each error category independently and therefore each case may have been flagged for multiple error cases.

Table 7 – Qualitative Analysis

	Plain-Only Probe Cases (Stitched)	Rolled-Only Probe Cases (None Stitched)
Number of Errors (FAP45 Subset Only)		
False Non Match Cases (count)	72	57
False Positive Cases (count)	15	14
Errors Common to Both Rolled and Plain Cases		
False Non Match Cases (count)	24	
False Positive Cases (count)	5	
Errors Unique to Rolled Or Plain Cases		
False Non Match Cases (count)	48	33
False Positive Cases (count)	10	9
Observed Coded Errors (False Negatives)	Count	Count
Quality Issue	31	30
Stitching Issue	19	0
Capture Issue	8	7
Scanner Defect	0	11
Reference database Poisoning	11	1
Reference database Quality Issue	1	2
Observed Coded Errors (False Positives)	Count	Count
Quality Issue	4	7
Stitching Issue	6	0
Scanner Defect	0	2
Capture Issue	1	0
Reference database Poisoning	1	0

8. Conclusion

We began our investigation by establishing a baseline performance measurement across all the data used in this investigation. In this case, the system exhibited an FNIR of 0.383% (n=199) and an FPIG of 0.106% (n=55).

Next, we limited our tests to just CAR transactions (n=13,196, which contain both plain and rolled impressions). In this scenario, CAR transactions performed slightly better in terms of both FNIR (0.371% vs 0.383%) and FPIG (0.076% vs 0.106%). This suggests that a combination of factors including having both rolled and plain impressions as well as more rigorous training of the personnel responsible for fingerprint collection may benefit the CAR transaction in terms of matcher performance.

Binning the CAR transactions (n=13,196) into FAP45 (n=9,855) and FAP50 (n=3,341) subsets shows that the small-platen FAP45 (stitched) is nearly on-par but with slightly better performance than FAP50 (not stitched) with respect to both FNIR (0.355% vs 0.419%), as well as FPIG (0.061% vs. 0.120%). Furthermore, FAP45 CAR-only transactions which included stitched images performed slightly better than the mix of all transactions with an FNIR (0.355% vs 0.383%), as well as FPIG (0.061% vs. 0.106%). This suggests that stitching in the scope of CAR transactions yields performance on par with, if not slightly better than, the general mix of Mobile ID transactions thereby disproving our hypothesis that stitching alone can markedly and negatively impact machine matching ability.

To see if this is true with other transaction types which may have only flat images (or only rolled images), we further partitioned the FAP45 CAR set (n=9,855) into two sets. The first set contains only the plain portion of the transaction (stitched), while the second set contains only the rolled portion of the transaction (not stitched). In this case, the results yielded a significant shift where the plain portion (possibly stitched) of the CAR transaction performed worse than the rolled portion (not stitched) in terms of both FNIR (0.731% vs 0.578%) and FPIG (0.152% vs 0.142%).

This suggests that while stitching may not severely impact CAR transactions specifically (as they are required to contain both a full set of plain impressions as well as a full set of rolled impressions), eliminating the rolled impressions leaving behind just the plain impressions points to stitching being a contributing factor to a performance penalty on the matcher.

To gain a better understanding of the underlying reasons for the failure cases impacting the plain (possibly stitched) and rolled (not stitched) impressions, a qualitative analysis of those failures was conducted. The qualitative analysis showed that the dominant qualitative issue present almost equally (n=31 and n=30) in both plain and rolled impressions was the image quality of the fingerprint impression. Next, stitching was the most prominent issue present (n=19, in subset containing plain-only images). This was followed by another interesting case, where the system reference database had incorporated an exemplar set containing stitching errors in a previous encounter (n=11, plain impressions) and defects as a result of scanner damage (n=11, rolled-only images).

This finding suggests that while including a full set of plain and rolled impressions can mitigate any large performance penalty as a result of stitching, errors such as rotation inversion could be

mitigated by operator training to safeguard the operation of the system when using stitched images.

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