Latent Fingerprint Matching
A Survey

Presented by
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Dr. Richa Singh

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INFORMATION TECHNOLOGY
DELHI

11/7/2013
Biometrics

- Use of distinctive anatomical and behavioral characteristics for automatically recognizing individuals.

Bertillonage, 1879

Fingerprint, 1893

Signature

Gait

Face

Iris

Voice

Images from various sources in internet
Fingerprints

• The pattern of interleaved ridges and valleys on the tip of the finger

“Perhaps the most beautiful and characteristic of all superficial marks are the small furrows with the intervening ridges and their pores that are disposed in a singularly complex yet even order on the under surfaces on the hands and the feet.”

Fingerprints - types

- Inked
- Live-scan
- Latent

Images from various sources in internet
Latent fingerprints

- Not immediately visible to human eyes
- Forensic applications – crime scene investigation
The big problem

Latent print

Exemplar prints

(a)  (b)  (c)

(d)  (e)
Common misunderstanding ...

It’s fiction !!!
A burglary remained unsolved for seven years – because fingerprints of the defendant weren’t of a good enough quality to link him to the case.

Challenges

- Availability of partial fingerprints
- Poor ridge quality
- Presence of background noise
- Non-linear ridge distortion
- Lack of databases
- Lack of experts
- Lack of scientific procedure
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- Lack of scientific procedure

NIST SD-27: 258 images

IIITD Latent: 1046 images
Challenges

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- Availability of partial fingerprints
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Image source: Internet
ACE-V Methodology

• ACE-V: Analysis, Comparison, Evaluation, Verification

• Structured guide for friction ridge prints
Human analysis of ACE-V

Effect of verification stage

<table>
<thead>
<tr>
<th>Research</th>
<th>Aim</th>
<th>#participants</th>
<th>#comparisons</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wertheim et al., 2006</td>
<td>Effect of verification in ACE-V</td>
<td>16</td>
<td>160</td>
<td>1. None of the expert were able to verify even one error.</td>
</tr>
<tr>
<td>Langenberg, 2009</td>
<td>Comparison of ACE and ACE-V</td>
<td>6</td>
<td>271</td>
<td>1. All 9 false positives detected during verification.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Number of erroneous exclusions doubled during verification.</td>
</tr>
</tbody>
</table>
## Human analysis of ACE-V

### Effect of additional information

<table>
<thead>
<tr>
<th>Research</th>
<th>Aim</th>
<th>#participant</th>
<th>#comparisons</th>
<th>Results</th>
</tr>
</thead>
</table>
| Dror et al., 2005    | Analyzing the bias of the examiner    | 27           | 2484         | 1. Manipulated with emotional stories and explicit photos.  
2. Increased likelihood matching for ambiguous fingerprints. |
| Dror and Charlton, 2006 | Consistency when provided additional information | 6            | 48           | 1. Only 33.3% of the trials were consistent.  
2. Reason – active and dynamic nature of human’s processing of information. |
| Hall and Player, 2008 | Consistency with emotional context    | 70           | -            | 1. Context did not have any effect on the final judgment of the experts. |
### Human analysis of ACE-V

#### Effect of context

<table>
<thead>
<tr>
<th>Research</th>
<th>Aim</th>
<th>#participant</th>
<th>#comparisons</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dror et al., 2006</td>
<td>Influence in decision by a context</td>
<td>5</td>
<td>-</td>
<td>1. Additional context saying “no-match”. 2. 80% of the examiners provided contradictory decisions.</td>
</tr>
<tr>
<td>Dror et al., 2011</td>
<td>Influence under the context of target full prints</td>
<td>20</td>
<td>200</td>
<td>1. During analysis, a variation of about $(2.6 \pm 3.5)$ minutiae was observed. 2. Feedback used to attune the examiner’s analysis strategies.</td>
</tr>
</tbody>
</table>
Take away ...

• Human examiners set very high threshold and are very cautious.

• Subjective and prone to inconsistencies.

• Studies show contradictory results.

• Not scalable for large scale latent fingerprint matching.
Need for an automated system?

- Quick and avoid inconsistencies.

- Ex: FBI’s Integrated Automated Fingerprint Identification System (IAFIS).

- Semi automated system – 74 million subject criminal gallery.

- Unsolved latent files till Feb, 2013 - 436,099
Latent fingerprint matching system
Latent fingerprint matching system

Level 1:
- Pattern Type
  - Fingerprint capture
  - Fingerprint enhancement
  - Feature extraction

Level 2:
- Human hand
- Quality assessment
- Fingerprint segmentation

Level 3:
- Pores, Dots, incipients, ridge flow map
- (a) Arch
- (b) Tented Arch
- (c) Left Loop
- (d) Right Loop
- (e) Twin Loop
- (f) Whorl

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Latent fingerprint matching system

Human hand → Fingerprint capture → Quality assessment → Fingerprint enhancement → Fingerprint segmentation → Feature extraction

\[
\begin{align*}
<x_1, y_1, \theta_1> \\
<x_2, y_2, \theta_2> \\
... \\
<x_n, y_n, \theta_n>
\end{align*}
\]
Latent fingerprint matching system

Human hand → Fingerprint capture → Quality assessment → Fingerprint enhancement → Fingerprint segmentation → Feature extraction → Feature matching → Match Scores → Individualization Decision

Enrolled database

\[
\begin{align*}
<x_1, y_1, \theta_1> \\
<x_2, y_2, \theta_2> \\
\vdots \\
<x_n, y_n, \theta_n>
\end{align*}
\]
Latent fingerprint matching system

11/7/2013
Common mis-understanding ...
## Databases

<table>
<thead>
<tr>
<th>Database</th>
<th>#Classes</th>
<th>#Images</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIST SD-27 (A)</td>
<td>258</td>
<td>258</td>
<td>1. Latent to rolled fingerprint matching&lt;br&gt;2. Manually annotated features available&lt;br&gt;3. 500ppi and 1000ppi exemplars</td>
</tr>
<tr>
<td>IIITD Latent fingerprint</td>
<td>150</td>
<td>1046</td>
<td>1. Latent, mated 500ppi and 1000ppi exemplar&lt;br&gt;2. Lifted using black powder dusting process&lt;br&gt;3. Captured directly using a camera</td>
</tr>
<tr>
<td>IIITD SLF</td>
<td>300</td>
<td>1080</td>
<td>1. Simultaneous latent with mated slap 500ppi&lt;br&gt;2. 2 sessions of simultaneous latent fingerprint&lt;br&gt;3. Latent fingerprint images have to be cropped</td>
</tr>
<tr>
<td>WVU latent fingerprint</td>
<td>449</td>
<td>449</td>
<td>1. Latent to rolled fingerprint matching&lt;br&gt;2. Manually annotated features available&lt;br&gt;3. 500ppi and 1000ppi exemplars</td>
</tr>
<tr>
<td>ELFT-EFS public challenge</td>
<td>1100</td>
<td>1100</td>
<td>1. 500ppi and 1000ppi images in WSQ format&lt;br&gt;2. Database not publicly available&lt;br&gt;3. Manually annotated features available</td>
</tr>
</tbody>
</table>
Latent fingerprint matching system
Latent quality assessment

- Direct predictor of matching performance

Global quality = 45

Local quality map
Latent fingerprint quality

- Quality is the measure of amount of matching information
### Latent quality assessment

<table>
<thead>
<tr>
<th>Research</th>
<th>Approach</th>
<th>Database</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yoon et al., 2012</td>
<td>Ridge continuity maps, number of minutiae</td>
<td>NIST-SD 27 +</td>
<td>1. 2 class – {VID, not-VID}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WVU</td>
<td>2. 60% classification accuracy for automatically extracted features.</td>
</tr>
<tr>
<td>NFIQ 2.0, 2013</td>
<td>Set of all features for quality</td>
<td>Proprietary</td>
<td>1. A score value of 1-100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Improved recognition error rate</td>
</tr>
<tr>
<td>Hicklin et al., 2013</td>
<td>Manual analysis of clarity and quality</td>
<td>Proprietary</td>
<td>1. Color coded clarity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Labeling inconsistent</td>
</tr>
</tbody>
</table>
Research challenges

• Automated quality and clarity assessment
• Local quality maps

![Local quality maps](image)

• Quality is more than number of minutiae
Latent fingerprint matching system
Latent fingerprint enhancement

Latent fingerprint

Coarse orientation field

Reference dictionary

Regularized orientation field
## Latent fingerprint enhancement

<table>
<thead>
<tr>
<th>Research</th>
<th>Approach</th>
<th>Database</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yoon et al., 2010</td>
<td>Orientation field regularization using “zero pole”</td>
<td>NIST-SD 27</td>
<td>1. Enhancement improves rank-1 accuracy from 20% to 35%</td>
</tr>
<tr>
<td>Yoon et al., 2011</td>
<td>Coarse orientation fitting using RANSAC</td>
<td>NIST-SD 27</td>
<td>1. Rank-1 matching accuracy from 12% to 26%</td>
</tr>
<tr>
<td>Feng et al., 2012</td>
<td>Dictionary of reference orientation patch</td>
<td>NIST-SD 27</td>
<td>1. Average estimation error in orientation is 18.44°</td>
</tr>
</tbody>
</table>
Research challenges

1. Noisy data

   Latent fingerprints

   After enhancement

2. Need for a metric to evaluate enhancement
Latent fingerprint matching system

Human hand → Fingerprint capture → Quality assessment → Fingerprint enhancement → Fingerprint segmentation → Feature extraction → Feature matching → Match Scores → Individualization Decision

Enrolled database
Latent fingerprint segmentation

- Background
- Foreground
Latent fingerprint segmentation

Challenges

- Speckle
- Line
- Arch
- Stain
- Character
Latent fingerprint segmentation

Features used:
1. Ridge orientation
2. Ridge frequency
3. Ridge correlation
4. Ridge texture
Latent fingerprint segmentation

<table>
<thead>
<tr>
<th>Research</th>
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<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karimi and Kuo, 2008</td>
<td>Ridge frequency estimation</td>
<td>2 images from NIST-SD 27</td>
<td>1. No quantitative results</td>
</tr>
<tr>
<td>Short et al., 2011</td>
<td>Cross-correlation strength</td>
<td>NIST-SD 27</td>
<td>1. Verification – EER of 33.8%</td>
</tr>
<tr>
<td>Zhang et al., 2012</td>
<td>Adaptive Total Variational (TV-L1) model</td>
<td>3 images from NIST-SD 27</td>
<td>1. No quantitative results</td>
</tr>
<tr>
<td>Zhang et al., 2012</td>
<td>Directional Total Variational (DTV) model</td>
<td>3 images from NIST-SD 27</td>
<td>1. No quantitative results</td>
</tr>
<tr>
<td>Choi et al., 2012</td>
<td>Orientation + frequency tensor</td>
<td>NIST-SD 27 and WVU DB</td>
<td>1. Rank-1 matching accuracy for NIST SD-27 : 16.28% WVU DB : 35.19%</td>
</tr>
</tbody>
</table>
Research challenges

1. Standard definition

   Input
   Bounding box
   Exact boundary
   Without smudges
   NFSEG
   Choi et al.

2. Metric to determine segmentation accuracy
Latent fingerprint matching system
Latent fingerprint feature extraction

- Automatic level-2 feature extractor for latent fingerprint is still an open research problem

- Challenges: Very poor quality and noisy data
# Level-1 features

<table>
<thead>
<tr>
<th>Research</th>
<th>Approach</th>
<th>Database</th>
<th>Results</th>
</tr>
</thead>
</table>
| Feng and Jain, 2008              | DB filtering using pattern type, singular point, orientation field | NIST-SD 27   | 1. Penetration rate of 39%  
2. Rank-1 matching performance from 70.9% to 73.3%                      |
| Su and Srihari, 2010             | Core point detection using Gaussian process         | NIST-SD 27   | 1. Core point prediction accuracy of 84.5%                              |
Level-2 and level-3 features

<table>
<thead>
<tr>
<th>Research</th>
<th>Approach</th>
<th>Database</th>
<th>Results</th>
</tr>
</thead>
</table>
| Puertas et al., 2010| Manual extraction with automatic extraction        | Proprietary    | 1. 6 (avg.) spurious minutiae per print  
2. Latent quality is an open problem |
| Paulino et al., 2010| Fuse automatic and manually marked minutiae        | NIST-SD 27     | 1. Boosted max score fusion gave max accuracy                                                                                           |
| Jain and Feng, 2011 | Singular points, ridge flow map, ridge wavelength | NIST-SD 27 (A) | 1. Rank-1 accuracy from 34.9% (only minutiae) to 74% (all features)  
2. Use level-3 only when level-2 fails |
## Other descriptors

<table>
<thead>
<tr>
<th>Research</th>
<th>Approach</th>
<th>Database</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vatsa et al., 2008</td>
<td>1. Pore and ridge with minutiae 2. RDWT based quality</td>
<td>Proprietary</td>
<td>1. Rank-1 identification accuracy of 87.5%</td>
</tr>
<tr>
<td>Paulino et al., 2013</td>
<td>1. Local descriptor based Hough transform 2. MCC code for minutiae</td>
<td>NIST SD-27</td>
<td>1. Rank-1 identification accuracy is 57.4%</td>
</tr>
</tbody>
</table>
Research challenges

1. Spurious minutiae

2. Explore additional latent specific features
Latent fingerprint matching system

- Human hand
- Fingerprint capture
- Quality assessment
- Fingerprint enhancement
- Fingerprint segmentation
- Feature extraction
- Feature matching
- Enrolled database
- Match Scores
- Individualization Decision
Latent fingerprint matching

• Increase inter-class variation and

Decrease intra-class variation
### Effect of fusion

<table>
<thead>
<tr>
<th>Research</th>
<th>Approach</th>
<th>Database</th>
<th>Results</th>
</tr>
</thead>
</table>
| Jain et al., 2008      | 1. Local minutiae matching  
2. Global minutiae matching                                                | NIST-SD 27    | 1. An rank-1 matching accuracy of 79.5% with weighted match score fusion                        |
| Feng et al., 2009      | 1. Rank level, match score level, feature level fusion                   | ELFT-EFS       | 1. Rank-1 identification accuracy of 83% from 57.8% for boosted-max fusion                       |
| Dvornychenko, 2012     | 1. Fusion of classifiers  
2. Fusion of features                                                          | Proprietary    | 1. Rank-1 matching performance boost of 6-15% for feature fusion                                |
## Latent fingerprint matching

### Performance of tenprint matchers

<table>
<thead>
<tr>
<th>Research</th>
<th>Approach</th>
<th>Database</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mikaelyan and Bigun, 2012</td>
<td>1. Establish ground truth in NIST SD-27</td>
<td>NIST-SD 27</td>
<td>1. EER of Bozorth3: 36% K-plet: 40%</td>
</tr>
<tr>
<td></td>
<td>2. K-plet and Bozorth3 (NBIS)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Research challenges

• Extraction of reliable valid features

• Research in feature extraction would drive research in feature matching

• Use of machine learning algorithms for matching
## Summary – state of the art

<table>
<thead>
<tr>
<th>Process</th>
<th>State of art</th>
<th>Technique</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality assessment</td>
<td>Yoon et al., 2012</td>
<td>Ridge clarity maps</td>
<td>Rank-100 improvement of 69% to 86% in combined NIST SD-27 and WVU database</td>
</tr>
<tr>
<td>Enhancement</td>
<td>Yoon et al., 2011</td>
<td>STFT + RANSAC</td>
<td>Rank-20 improvement from 10% to 51% in NIST SD-27</td>
</tr>
<tr>
<td></td>
<td>Feng et al., 2012</td>
<td>Dictionary of orientation patches</td>
<td>Rank-20 matching accuracy of 35% in NIST SD-27</td>
</tr>
<tr>
<td>Segmentation</td>
<td>Choi et al, 2012</td>
<td>Orientation and frequency tensor</td>
<td>Rank-1 identification accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.  NIST SD-27: 16.28%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.  WVU DB: 35.19%</td>
</tr>
<tr>
<td>Feature extraction</td>
<td>Paulino et al., 2013</td>
<td>Hough transform + MCC</td>
<td>Rank-1 accuracy of 57.4% in combined NIST SD-27 and WVU database</td>
</tr>
<tr>
<td>Feature matching</td>
<td>Jain and Feng, 2011</td>
<td>Local and global matching</td>
<td>Rank-1 accuracy of 74% on NIST SD-27 (A)</td>
</tr>
</tbody>
</table>
My research directions

Challenge: Lack of data

IIITD Latent
- Latent with 500 and 1000ppi flat
- Captured directly using camera
- 1046 images, 150 classes

IIITD SLF
- Simultaneous latent fingerprint
- Latent images can be cropped
- 1080 images, 300 classes

IIIT MOLF
- Three sensors, latent and multiple latent
- 1000 classes and more than 20000 images

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My research directions

Challenge: Automatic quality assessment

Local clarity assessment

Local quality assessment

Enrolled database
My research directions

1. Binary classification problem
2. Foreground ridge pattern representation
3. RDF based classification

Challenge: Automatic segmentation

- Human hand
- Fingerprint capture
- Quality assessment
- Fingerprint enhancement
- Fingerprint segmentation
- Feature extraction
- Feature matching
- Match Scores
- Individualization Decision

Enrolled database

Input
Ground truth
Proposed algorithm

11/7/2013
My research directions

- Fingerprint capture
- Fingerprint enhancement
- Feature extraction
- Feature matching
- Match Scores
- Individualization Decision

- Enrolled database

11/7/2013
<table>
<thead>
<tr>
<th>Courses – CGPA: 9.5/10</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Probability and statistics</td>
</tr>
<tr>
<td>• Image analysis</td>
</tr>
<tr>
<td>• Introduction to biometrics</td>
</tr>
<tr>
<td>• Pattern recognition</td>
</tr>
<tr>
<td>• Machine learning</td>
</tr>
<tr>
<td>• Computer vision</td>
</tr>
<tr>
<td>• Technical communication (audit)</td>
</tr>
<tr>
<td>• Information retrieval</td>
</tr>
<tr>
<td>• Probabilistic graphical model (independent study)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Teaching assistant:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Probability and statistics</td>
</tr>
<tr>
<td>• Machine learning</td>
</tr>
<tr>
<td>• Data structures and algorithms</td>
</tr>
<tr>
<td>• Pattern recognition</td>
</tr>
</tbody>
</table>
Awards and recognition

- TCS Research Scholarship (2010-2014)
- Selected for BTAS – 2013 and BTAS – 2012 doctoral consortium
- Reviewer of
  - Information Fusion (Elsevier)
  - ICB – 2013
  - BTAS - 2013
Publications


Thank you

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Latent fingerprint matching
Latent fingerprint matching system

Latent fingerprint matching system

- Human hand
- Fingerprint capture
- Quality assessment
- Fingerprint enhancement
- Fingerprint segmentation
- Feature extraction

- \((x_1, y_1, \theta_1)\)
- \((x_2, y_2, \theta_2)\)
- ...
- \((x_n, y_n, \theta_n)\)
Latent fingerprint matching system

Human hand → Fingerprint capture → Quality assessment → Fingerprint enhancement → Fingerprint segmentation → Feature extraction → Feature matching → Match Scores → Individualization Decision

Subject ID

\[
\langle x_1, y_1, \theta_1 \rangle \\
\langle x_2, y_2, \theta_2 \rangle \\
... \\
\langle x_n, y_n, \theta_n \rangle
\]

Enrolled database

\[
98 \\
45 \\
78 \\
12 \\
5 \\
37
\]
Concluding remark #1

Forensic experts

Computational and technology aided techniques

AFIS

Human cognition

Images from various sources in internet
## Concluding remark #2

<table>
<thead>
<tr>
<th>Process</th>
<th>Features used in literature</th>
<th>Evaluation metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segmentation</td>
<td>1. Orientation tensor, frequency tensor [47]</td>
<td>1. Missed Detection Rate</td>
</tr>
<tr>
<td></td>
<td>2. Correlation strength [44]</td>
<td>2. False Detection Rate</td>
</tr>
<tr>
<td></td>
<td>4. Directional total variation (TV-L2) [46]</td>
<td></td>
</tr>
<tr>
<td>Quality Assessment</td>
<td>1. NFIQ1.0 features, frequency domain analysis, local clarity analysis, orientation flow,</td>
<td>1. VID and non-VID classification</td>
</tr>
<tr>
<td></td>
<td>radial power spectrum, ridge valley uniformity, Gabor filters, and minutiae count [54]</td>
<td>2. Rank-K matching of different quality bins</td>
</tr>
<tr>
<td></td>
<td>2. Gabor filters [55]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Ridge clarity map, number of minutiae [56]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Candidate orientation map, singular points [59, 58]</td>
<td>2. Rank-K matching of different quality bins</td>
</tr>
<tr>
<td>Matching</td>
<td>1. Singular points, ridge flow map, ridge wavelength map, ridge quality map, fingerprint</td>
<td>1. Rank-K matching</td>
</tr>
<tr>
<td></td>
<td>skeleton, minutiae points, ridge correspondence, level-3 features [69]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Orientation field, ridge flow, quality map, manual minutiae [72]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. MCC descriptor for minutiae [48]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Manually and automated extracted minutiae [68, 67]</td>
<td></td>
</tr>
</tbody>
</table>