CSE 40537 / 60537: Biometrics

Fingerprint Recognition 5
How'm I doin'?
Use of grayscale images

1. **Ridge Tracing** (Maio and Maltoni IEEE T-PAMI 1997)
   - Modification 1: adaptive step and binarization threshold (Jiang et al. PR 2001)
   - Modification 2: simultaneous tracking of a ridge and the neighboring valleys (Liu et al. ICIP 2000)

2. **Gabor wavelet features** + non-linear classification, e.g., non-linear neural network (Leung et al. IJCNN 1999)

3. **Gaussian Mixture Models** for local histogram modeling (Chang and Fan PR 2001)

4. **Local symmetry** of the image (Nilsson and Bigun AVBPA 2001)
Use of binary images

1. **Binary Image Generation**
   - Use of a global intensity threshold (simple, but low quality)
   - Use of a local or adaptive intensity threshold (may be preceded by ridge and valley enhancement)
   - Decomposition of a local histogram in directions orthogonal to ridges (Ratha et al. PR 1995)

2. **Ridge Tracing** (easier than in grayscale image)
Use of skeletal images

1. Thinning of the binary image
   - Solutions inspired by methods used in map vectorization and handwriting recognition
   - Popular solution are based on mathematical morphology (e.g., multiple erosions)
Use of skeletal images

2. Smoothing of the skeletal image
   • Removing very short ridges
   • Removing very short joints
   • Joining very short ridge breaks
3. **Simple analysis of neighboring pixels**

Number of neighboring ridge pixels provides the answer:

- $= 1$ : ridge ending
- $= 2$ : ridge (no minutiae)
- $\geq 3$ : bifurcation
4. **Minutiae Filtering**: removal of spurious minutiae

- Heuristic methods
  - Remove minutiae located at boundaries
  - Remove constellations of minutiae
- Duality of minutiae: simultaneous processing of positive and negative images (Hung PR 1993)
Example Minutiae Map

Minutiae directions compliant to ISO/IEC FDIS 19794-2 (2011)
Minutiae Matching

1. Compensation for linear deformations
   • Find a linear mapping between the probe and reference maps of minutiae
Minutiae Matching

2. Compensation for non-linear deformations

• **Popular and easy**: setting the tolerance box, a margin of acceptable difference between properties of two minutiae

• **More accurate, yet time consuming**: surface warping (Capelli et al. ICAPR 2001)

• **Interesting**: use of canonical form of the skeletal images (Senior and Bolle IEICE T-IS 2001)
Minutiae Matching

1. Calculation of matching score
   - popular: \( \frac{\text{number of minutiae that match}}{\text{average number of minutiae in both maps}} \)
   - Modifications:
     - In denominator: number of elements in the common set of minutiae maps
     - Minutiae weighting, depending on their quality
Mathematical definition of the problem

Minutiae sets:

\[ T = \{ m_1, m_2, \ldots, m_M \}, \quad m_i = \{ x_i, y_i, \theta_i \}, \quad i = 1, \ldots, M \]

\[ P = \{ m'_1, m'_2, \ldots, m'_N \}, \quad m'_j = \{ x'_j, y'_j, \theta'_j \}, \quad j = 1, \ldots, N \]

Two minutiae match if:

\[ s(m'_j, m_i) = \sqrt{(x'_j - x_i)^2 + (y'_j - y_i)^2} \leq r_0 \quad \text{distance in space} \]

\[ d(m'_j, m_i) = \min(|\theta'_j - \theta_i|, 360^\circ - |\theta'_j - \theta_i|) \leq \theta_0 \quad \text{similarity of rotation} \]
Finding a mapping function

\[ f : m'_j \mapsto m''_j \]

\[ m'_j = \{x'_j, y'_j, \theta'_j\}, \quad m''_j = \{x''_j, y''_j, \theta'_j + \theta\}, \quad j = 1, \ldots, N \]

Typically only rotation and shift are used, that is:

\[
\begin{bmatrix}
  x''_j \\
  y''_j
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
  x'_j \\
  y'_j
\end{bmatrix}
+ \begin{bmatrix}
  \Delta x \\
  \Delta y
\end{bmatrix}
\]
Aim Function

\[
\max_{\Delta x, \Delta y, \theta, p} \sum_{i=1}^{N} h \left( f_{\Delta x, \Delta y, \theta}(m'_{p(i)}), m_i \right)
\]

where

\[
h(m''_j, m_i) = \begin{cases} 
1 & \text{if } s(m''_j, m_i) \leq r_0 \text{ and } d(m''_j, m_i) \leq \theta_0 \\
0 & \text{otherwise}
\end{cases}
\]

and \( p \) defines the minutiae correspondence in the maps \( \mathcal{T} \) and \( \mathcal{P} \)
A few notes on the $p$ function

• $p(i) = j$ does not mean that two minutiae “match” in $h$ sense

• $p(i) = j$ when $m_i \in T$ has a correspondent minutiae $m'_j \in \mathcal{P}$

• when $p(i) \neq j$ for $i = 1, \ldots, M$ then minutia $m'_j \in \mathcal{P}$ has no corresponding minutiae in $T$
A few notes on the $p$ function

• $p$ is a bijection: each minutiae point $m'_j \in P$ has a single correspondent minutiae $m_i \in T$ (and minutiae that have no correspondence are skipped)

• In practice $p$ is unknown, and brute force solutions yield exponential calculation times
Compensation for linear distortions

Possible approach: Hough Transform

Co-linear points are mapped onto curves that have a common point of intersection

Image Credit: K. Pentenrieder
Hough Transform

• Popular and Fast

• Converts point-pattern matching problem into detecting peaks in Hough space
  ‣ Point-patterns in fingerprint space: location, rotation, and scale of the minutiae maps

Paulino et al. IJCB 2011
Hough Transform

• Independent “experts” vote for the best combination of discretized parameter values
  ‣ Each expert increases elements in the discretized parameter space, depending on its “expertise”

• Maximum element of the accumulator space suggests the winning combination of the discretized parameters
Hough Transform Example

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<tr>
<td>0</td>
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<tr>
<td>30</td>
<td>69.6</td>
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<td>70</td>
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<td>120</td>
<td>40.6</td>
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<tr>
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<td>120</td>
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<td>6.0</td>
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<tr>
<td>150</td>
<td>-39.6</td>
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Assumptions for Hough Transform

• Transformation defined by the quadruple \((\Delta x, \Delta y, \theta, s)\): shift, rotation, and scale

• We use discretized values of \(\Delta x, \Delta y, \theta, s\), namely: \(\Delta x^+, \Delta y^+, \theta^+, s^+\)
Using the accumulator

\[ A[\Delta x^+, \Delta y^+, \theta^+, s^+] = 0 \] for all \( \Delta x^+, \Delta y^+, \theta^+, s^+ \)

Accumulator \( A \) is a multi-dimensional array storing minutia information
Using the accumulator

for every \( m_i \), for every \( m_j \), for every \( \theta^+ \)

\[
\text{if } d(\theta'_j + \theta^+, \theta_i) \leq \theta_0 \\
\text{for every } s^+ \\
\begin{bmatrix}
\Delta x \\
\Delta y
\end{bmatrix} =
\begin{bmatrix}
x_i \\
y_i
\end{bmatrix} -
\begin{bmatrix}
s^+ \\
\cos \theta^+ & -\sin \theta^+ \\
\sin \theta^+ & \cos \theta^+
\end{bmatrix}
\begin{bmatrix}
x'_j \\
y'_j
\end{bmatrix}
\]

\( \Delta x^+ = \text{quantization}(\Delta x) \), \( \Delta y^+ = \text{quantization}(\Delta y) \)

\[
A[\Delta x^+, \Delta y^+, \theta^+, s^+] = A[\Delta x^+, \Delta y^+, \theta^+, s^+] + 1
\]
Winning combination of discretized parameters

\[
(\Delta x^*, \Delta y^*, \theta^*, s^*) = \arg\max_{\Delta x^+, \Delta y^+, \theta^+, s^+} A(\Delta x^+, \Delta y^+, \theta^+, s^+)
\]
Useful modifications

1. Simultaneous weighted incrementation of $A(\Delta x^+, \Delta y^+, \theta^+, s^+)$ and its neighbors

2. Use of parallel computing (parallelization of Hough transform is easy)

3. Coarse-to-fine approaches
Open Research Questions
Common Assumption: Fingerprint Recognition is Solved

- Open Problems
  - Usability: Quality Assessment, Systems Engineering
  - Forensics: Latent matching
  - Security and Privacy: Template Protection, Anti-spoofing
Longitudinal study of fingerprint recognition

Yoon and Jain PNAS 2015

- Fundamental premise of fingerprint-based identification: **persistence and uniqueness**
  - Not well studied

Assessment of commercial matchers and 15,597 subjects
Stability of fingerprint matches over time
Population mean trend

Probability of true acceptance, at operational FAR, remains close to 1
Population-mean trend and 95% confidence interval of probability of true acceptance

High Quality

Low Quality
Conclusions

• Genuine match scores decrease as the time interval between two fingerprints being compared increases.

• Genuine match scores decrease as the subject’s age increases, or when the fingerprint image quality decreases.

• Probability of true acceptance at operational FAR settings remains close to 1.
  - If either of two fingerprints in comparison is of poor quality, the uncertainty in the expected probability of true acceptance becomes considerably large.