

Fingerprint Biometric: Algorithms, Performance & Applications



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Course Outline

- Session I:

- History of fingerprints
- Fingerprint sensors
- Matching vs classification
- Minutiae-based matching
- Fingerprint enhancement

- Session II:

- Texture-based matching
- Fingerprint Mosaicking
- Classification schemes
- Deformation models

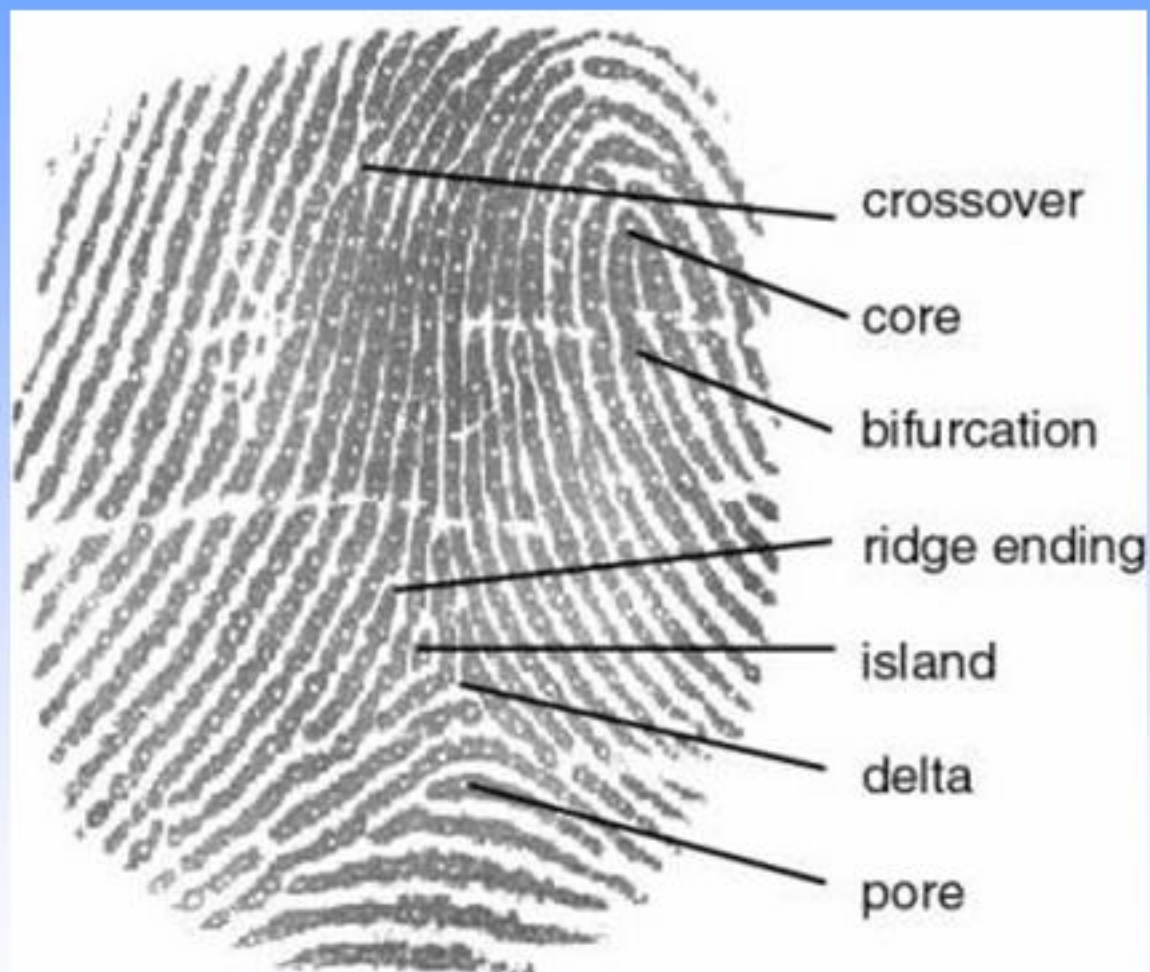
Fingerprint as a Biometric

Fingerprints



- **Description:** graphical flow like ridges present in human fingers
- **Formation:** during embryonic development
- **Permanence:** minute details do not change over time
- **Uniqueness:** believed to be unique to each finger
- **History:** used in forensics and has been extensively studied

Fingerprints



FACES CAN LIE.

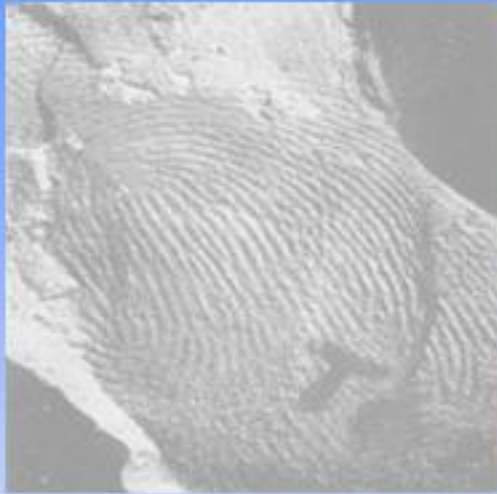


FINGERPRINTS, NEVER.

History of Fingerprints

- Many impressions of fingers have been found on ancient pottery
- Grew (1684): first scientific paper on ridges, furrows & pore structures
- Mayer (1788): detailed description of anatomical formation of fingerprints
- Bewick (1809): used his fingerprint as his trademark
- Purkinje (1823): classified fingerprints into 9 categories based on ridges
- Herschel (1858): used fingerprints on legal contracts in Bengal
- Fauld (1880): suggested "scientific identification of criminals" using fingerprints
- Vucetich (1888): first known user of dactylograms (inked fingerprints)
- Scotland Yard (1900): adopted Henry/Galton system of classification
- FBI (1924) set up a fingerprint identification division with a database of 810,000 fingerprints
- FBI (1965): installed AFIS with a database of 810,000 fingerprints
- FBI (2000): installed IAFIS with a database of **47 million 10 prints**; conducts an average of 50,000 searches/ day; ~15% of searches are in **lights out** mode. Response time: 2 hours for criminal search and 24 hours for civilian search

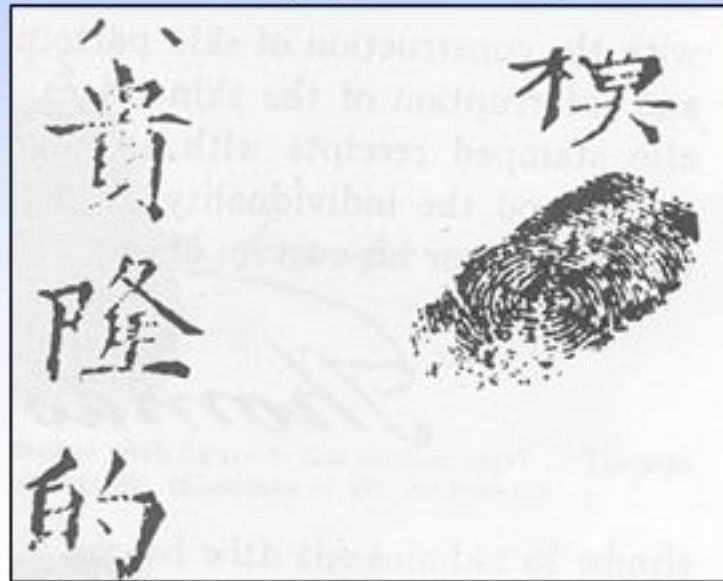
History of Fingerprints



Fingerprint on Palestinian lamp (400 A.D.)



Bewick's trademark (1809)



A Chinese deed of sale (1839) signed with a fingerprint

Fingerprint Sensors

- Optical, capacitive, ultrasound, pressure, thermal, electric field, 3D



Same Finger, Different Sensors



Crossmatch Verifier 300



**Ethenticate USB
2500**



**Secugen Hamster
III**



**Precise
100AX**



**Digital Persona
U.are.U 4000**

Fingerprint Acquisition Methodology



Flat Fingerprint

(One-touch print from a single-finger livescan device)



Slap Fingerprint

(4-finger simultaneous impression from livescan devices or scanned from paper FP cards)



Rolled Fingerprint

(Image collected by rolling the finger across the livescan platen or paper from nail to nail)

Fingerprint Matching

- Find the **similarity** between two fingerprints



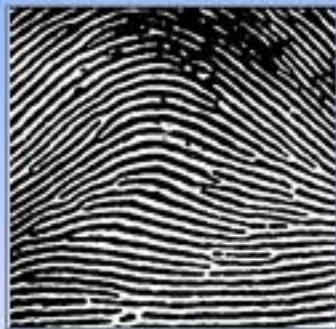
Fingerprints from the same finger



Fingerprints from two different fingers

Fingerprint Classification

- Assign fingerprints into one of pre-specified types



Plain Arch



Tented Arch



Right Loop



Left Loop



Accidental



Pocket Whorl



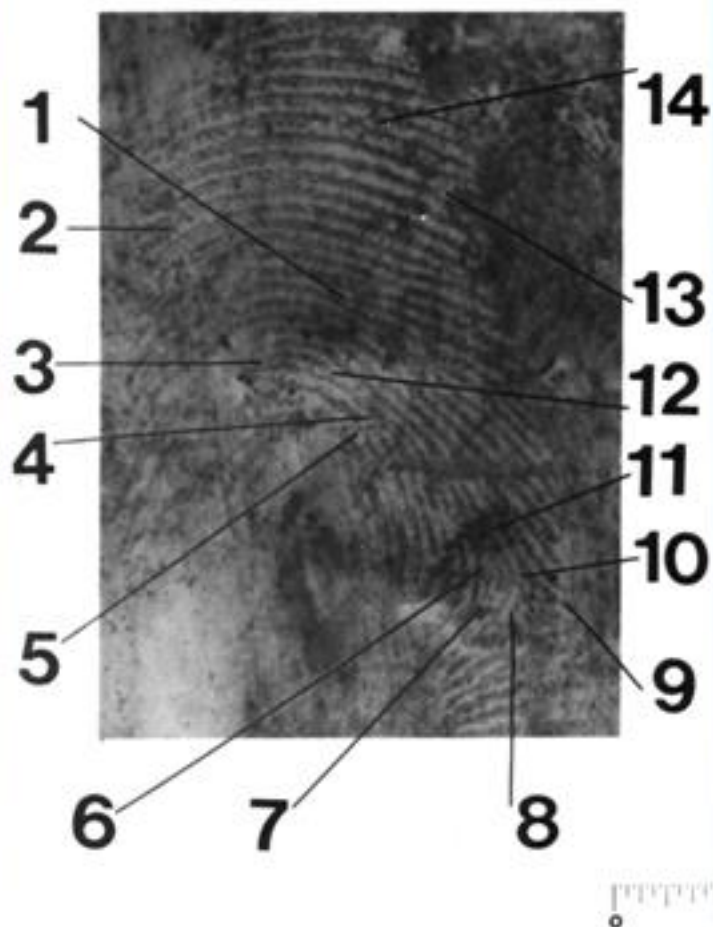
Plain Whorl



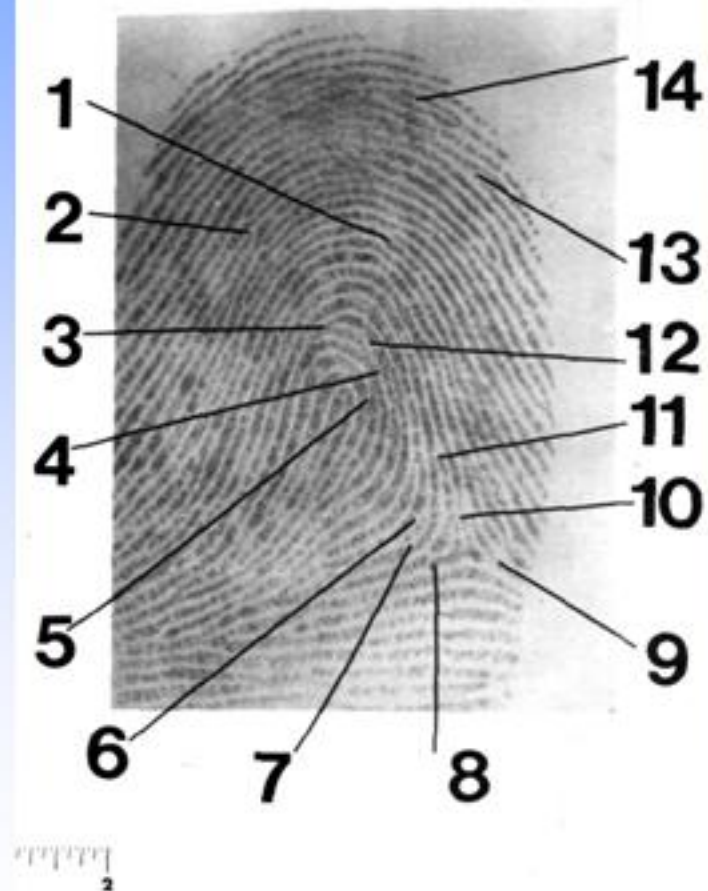
Double Loop

Minutiae-based Representation

LATENT FINGERPRINT

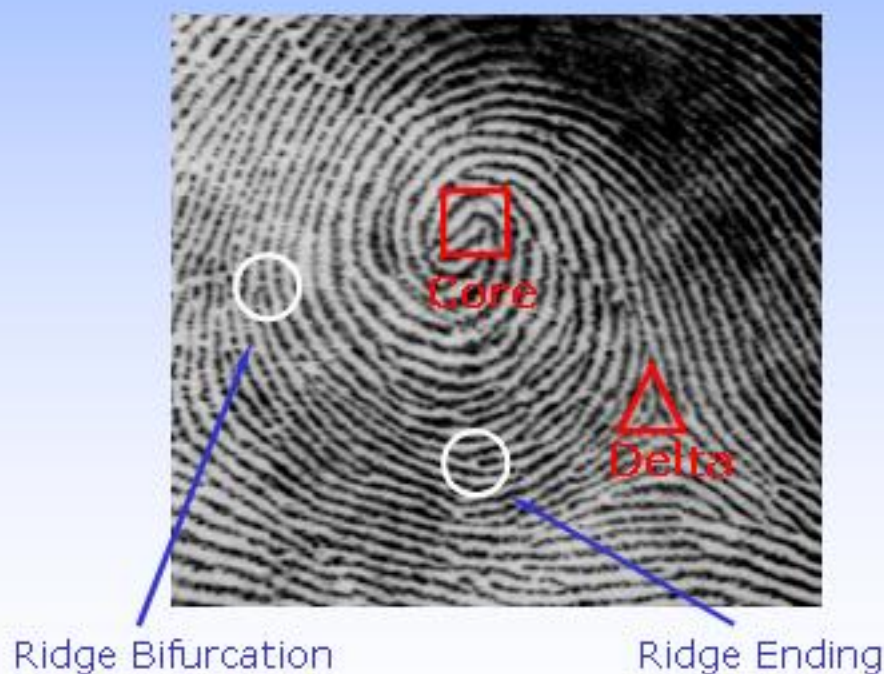


INKED FINGERPRINT










Ridge Anomalies

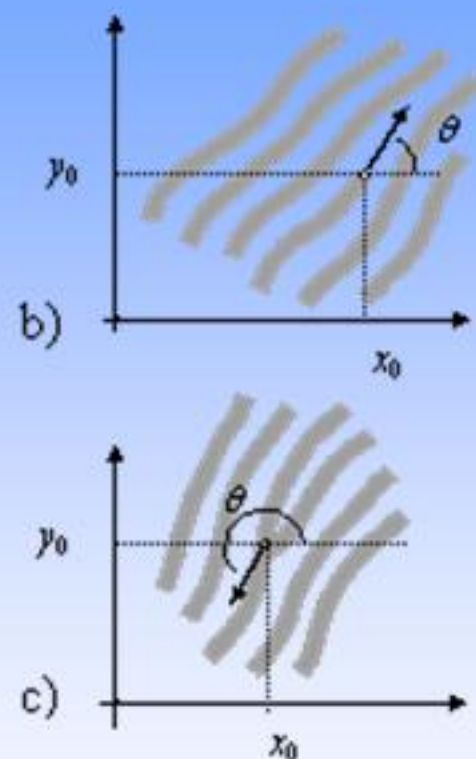
- Local ridge characteristics (**minutiae**): ridge ending and ridge bifurcation
- Singular points: Discontinuity in ridge orientation



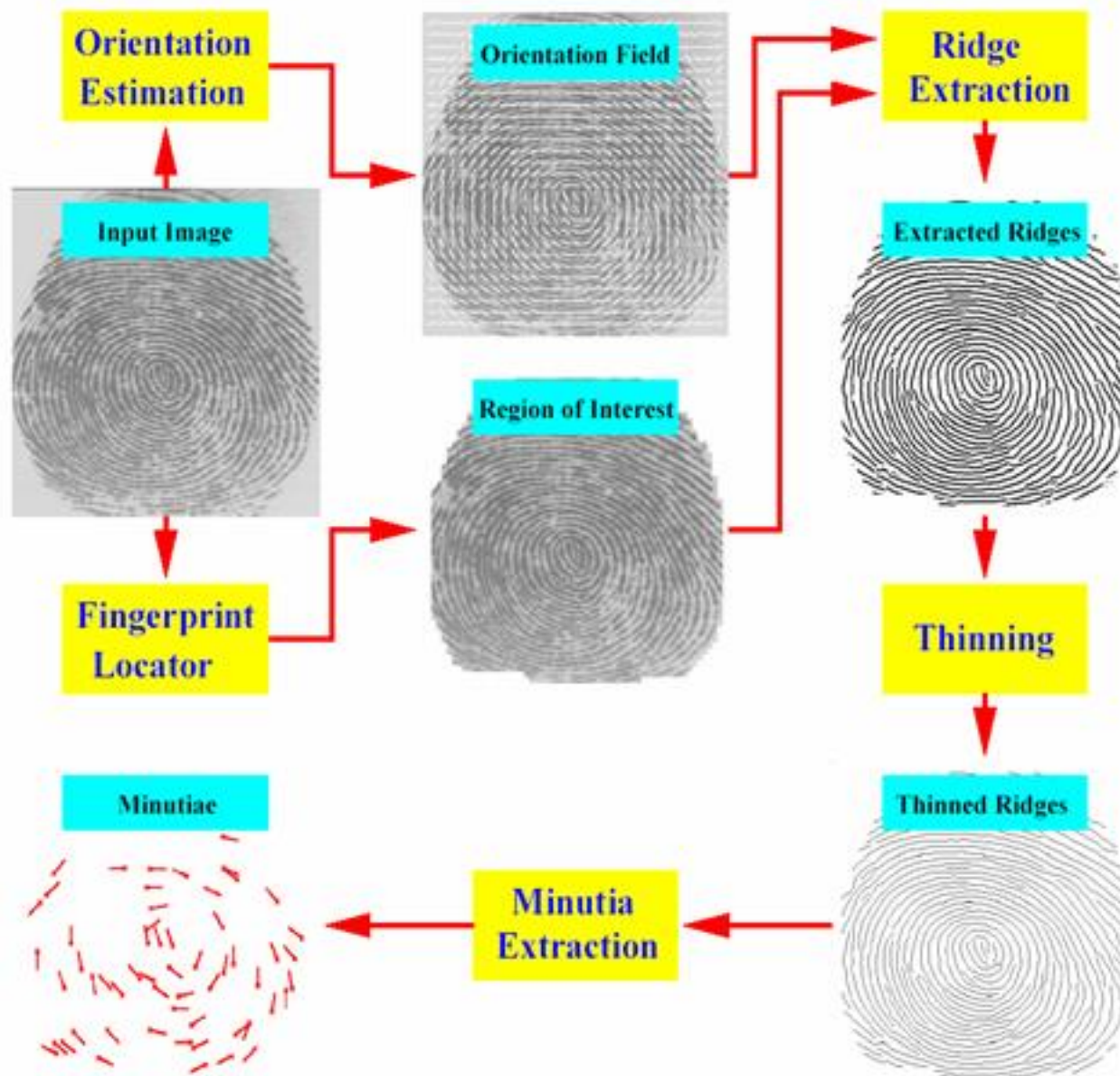
Minutiae Details

a)

	Termination
	Bifurcation
	Lake
	Independent ridge
	Point or island
	Spur
	Crossover



Minutia extraction algorithm



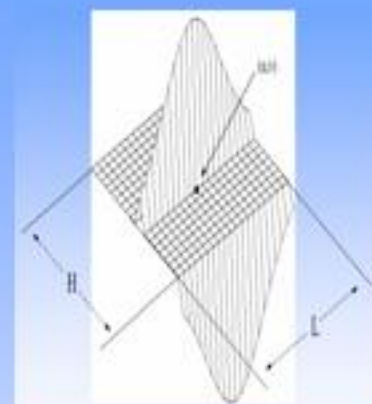
Minutiae Extraction



Input Image



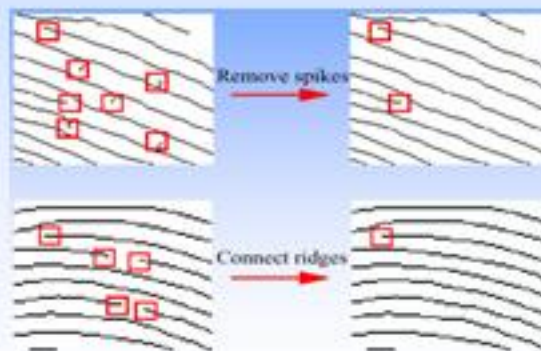
Orientation Estimation



Ridge Filter



Minutiae Extraction



Postprocessing



Ridge Thinning
Minutiae Detection

Orientation field estimation algorithm

- Divide the input fingerprint image into non-overlapping blocks of size $W \times W$
- Compute the gradients $G_x(i, j)$ and $G_y(i, j)$ at each pixel (i, j) using Sobel or Marr-Hildreth operator
- Least squares estimate of the local orientation of the block centered at (i, j) is

$$\theta(i, j) = \left(\frac{1}{2}\right) \tan^{-1} \left(\sum_{u=i-\frac{W}{2}}^{i+\frac{W}{2}} \sum_{v=j-\frac{W}{2}}^{j+\frac{W}{2}} \frac{2G_x(u, v)G_y(u, v)}{G_x^2(u, v) - G_y^2(u, v)} \right)$$

Orientation field estimation algorithm

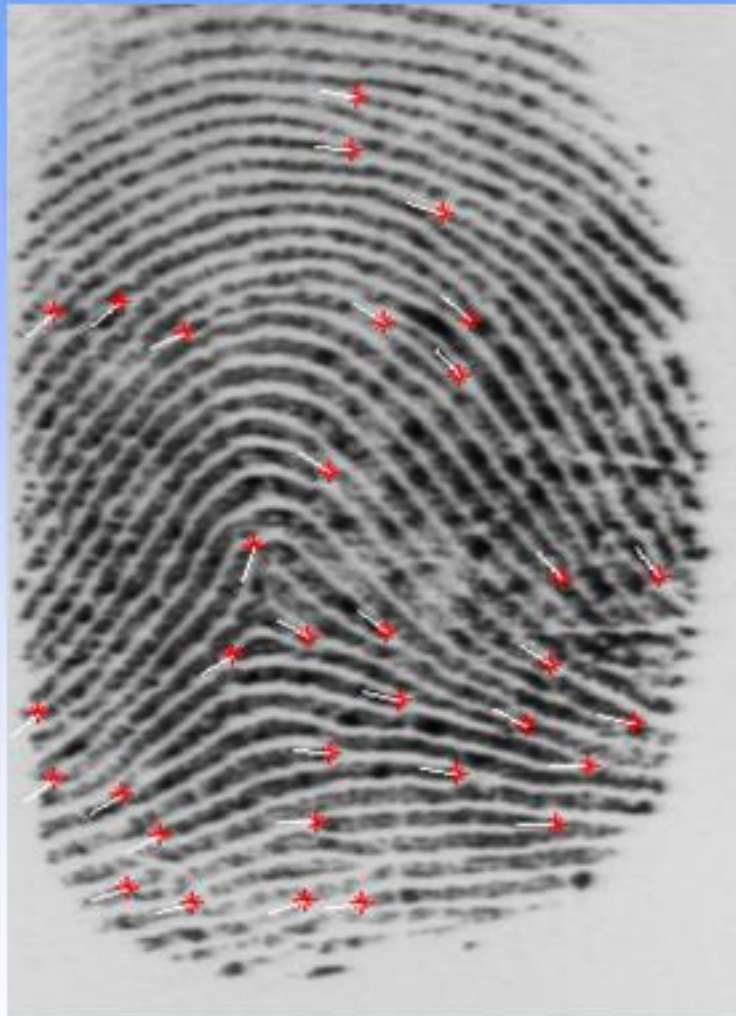
- Local ridge orientation varies slowly in a neighborhood where no singular points appear
- A low-pass filter can be applied to modify the local ridge orientation
- To apply low pass filter the orientation image is converted into a continuous vector field

$$\Phi_x(i, j) = \cos[2\theta(i, j)]$$

$$\Phi_y(i, j) = \sin[2\theta(i, j)]$$

$$O(i, j) = \left(\frac{1}{2}\right) \tan^{-1} \left(\frac{\Phi'_x(i, j)}{\Phi'_y(i, j)} \right)$$

Minutiae Template

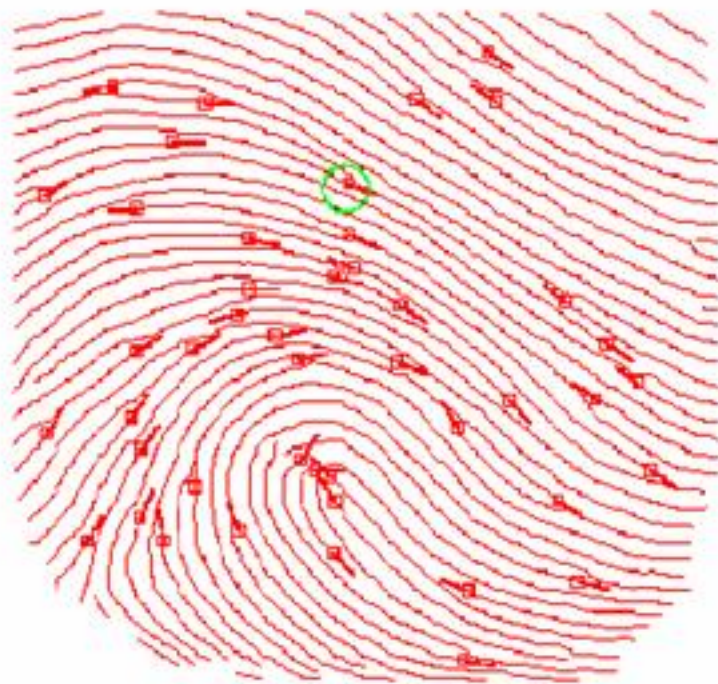


Fingerprint

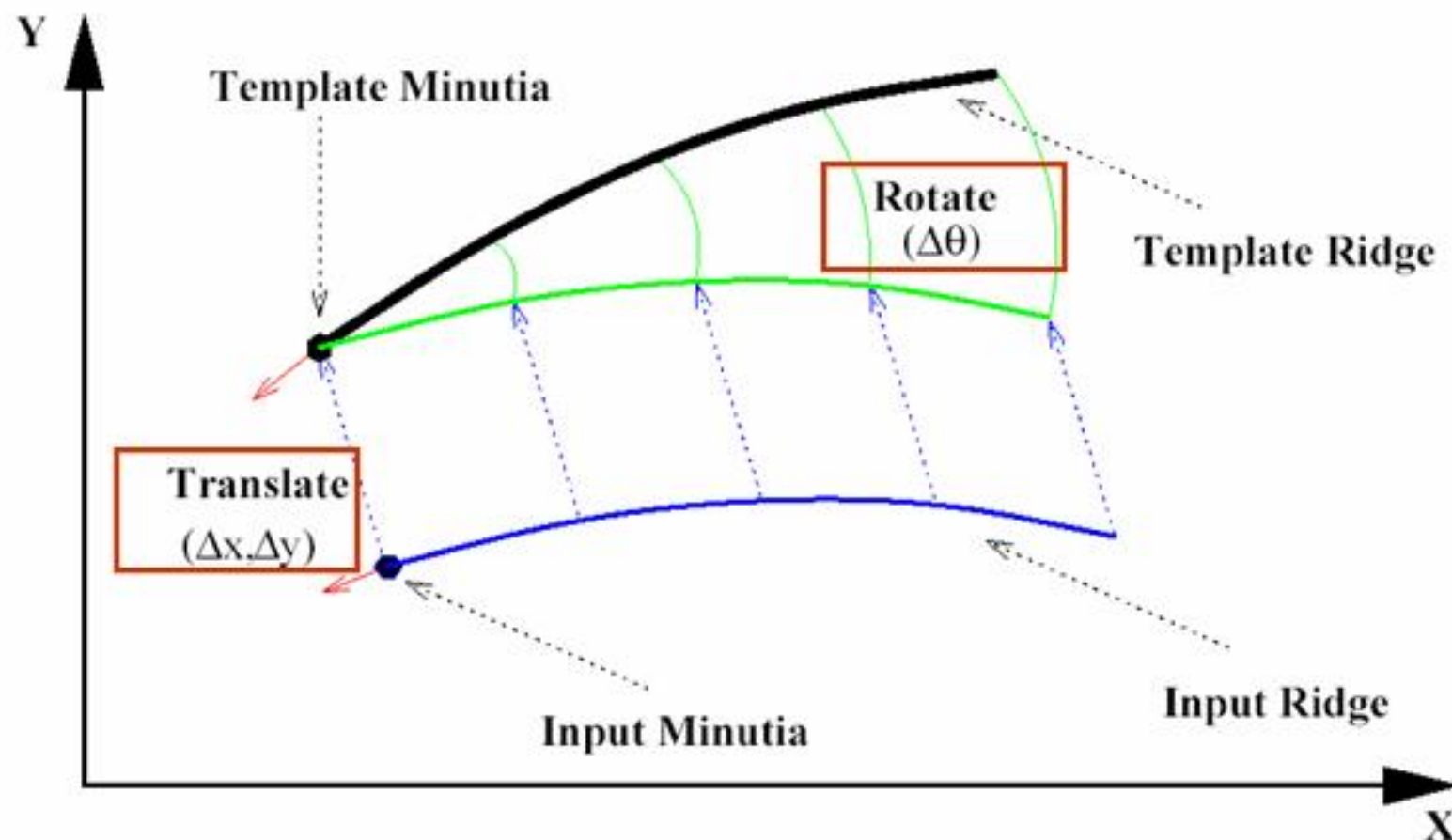
Number	X Coordinate	Y Coordinate	Angle
1	43	312	328
2	18	306	323
3	12	280	320
4	57	328	331
5	84	257	328
6	92	214	108
7	66	130	336
8	42	118	140
9	18	122	320
10	128	58	187
11	130	37	11
12	162	83	19
13	172	125	222
14	140	126	34
15	168	147	230
16	120	185	214
17	206	227	230
18	202	261	214
19	193	285	208
20	167	304	191
...

Template

Minutiae Point Pattern Matching



Alignment of Input and Template Ridges



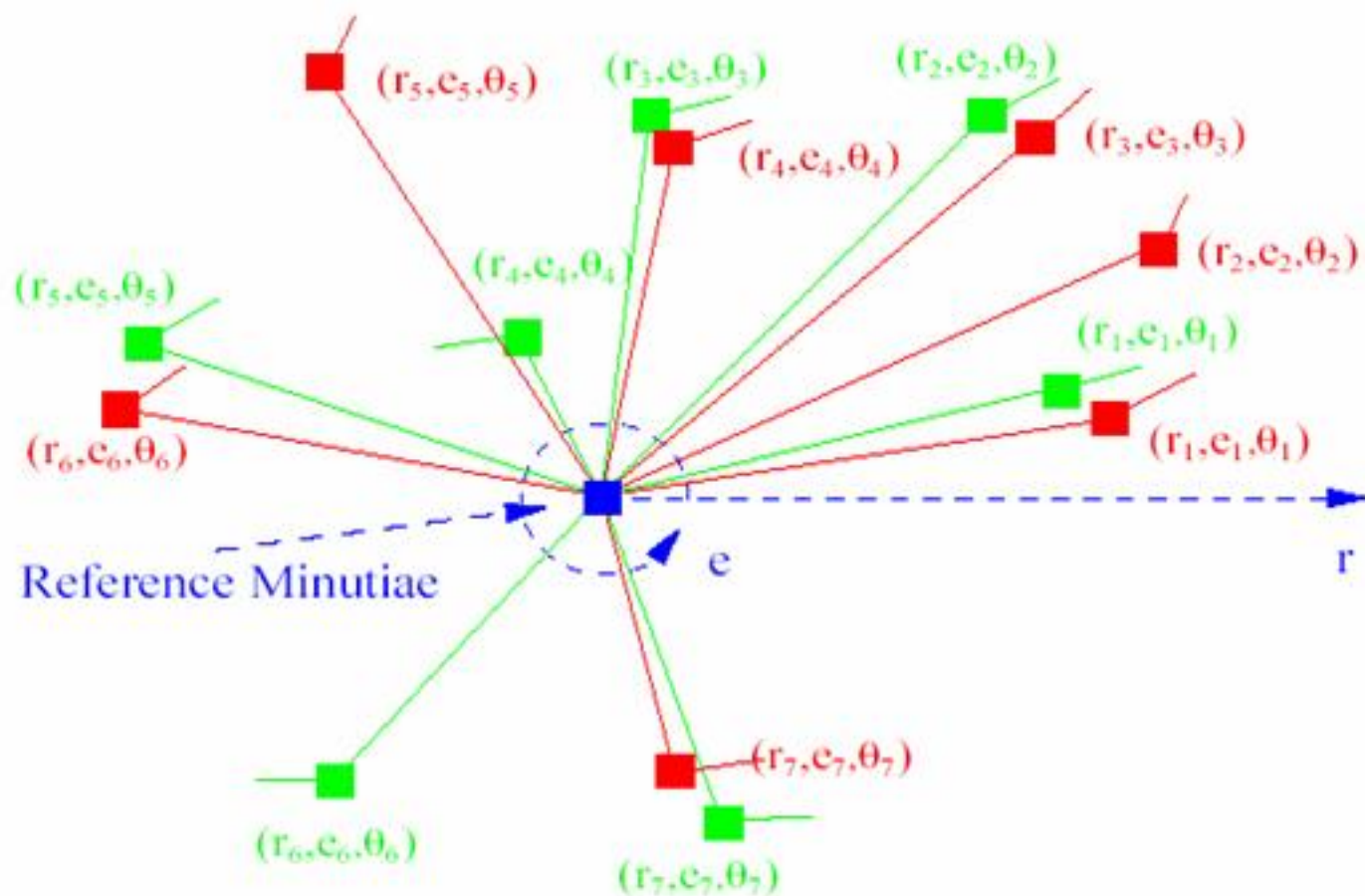
Matching Algorithm

- Estimate the rotation and translation parameters and align the two minutiae patterns
- Convert the template and input patterns into the polar coordinate system with respect to the reference minutiae and represent them as strings by concatenating each minutia in an increasing order of radial angles

$$P_p = \{(r_1^P, e_1^P, \theta_1^P), \dots, (r_M^P, e_M^P, \theta_M^P)\}$$

$$Q_p = \{(r_1^Q, e_1^Q, \theta_1^Q), \dots, (r_N^Q, e_N^Q, \theta_N^Q)\}$$

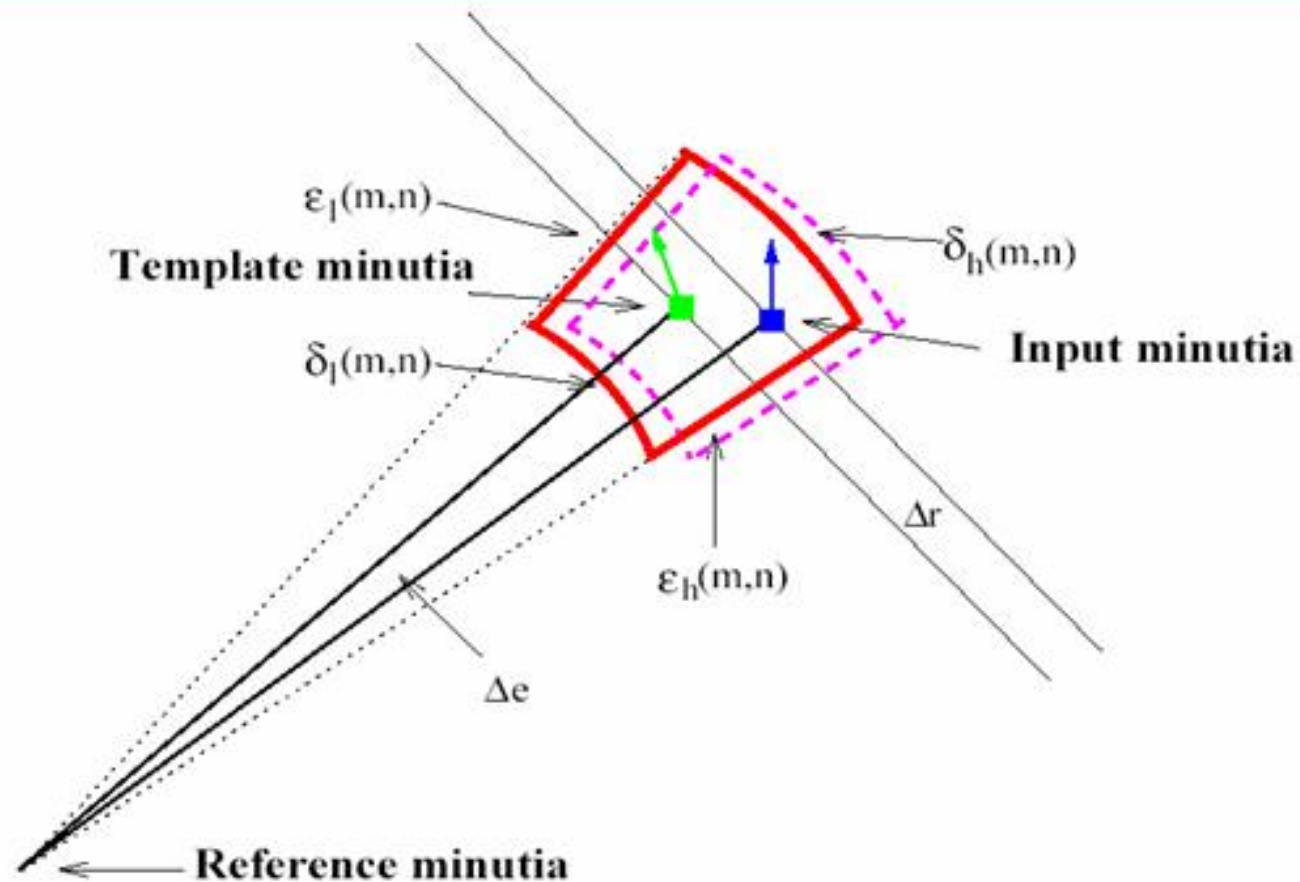
String Representation



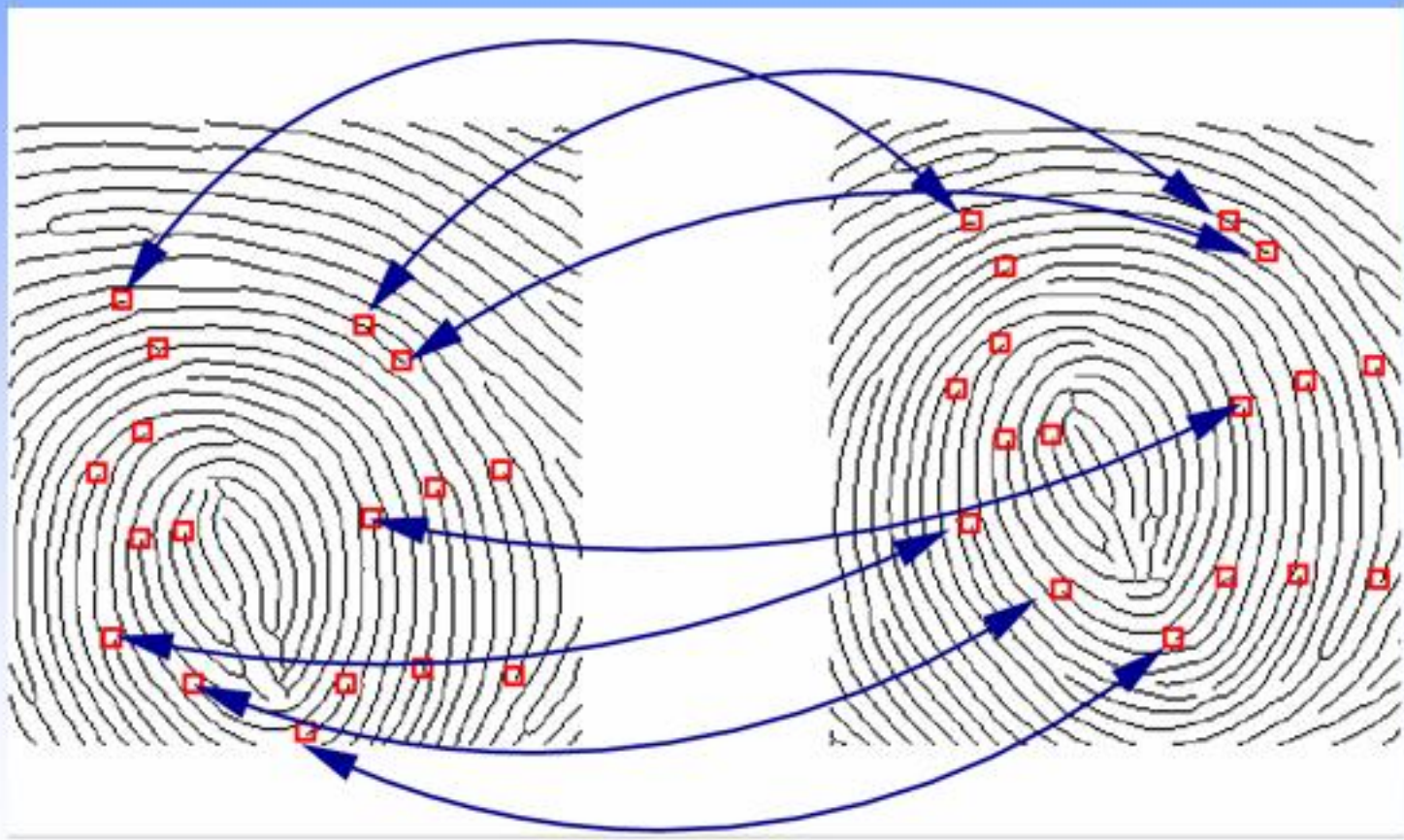
String Matching

- Match the strings P_p and Q_p with a modified dynamic programming algorithm to find the edit distance
- Edit distance must have the elastic property of string matching

Bounding Box Adjustment



Minutiae Correspondences

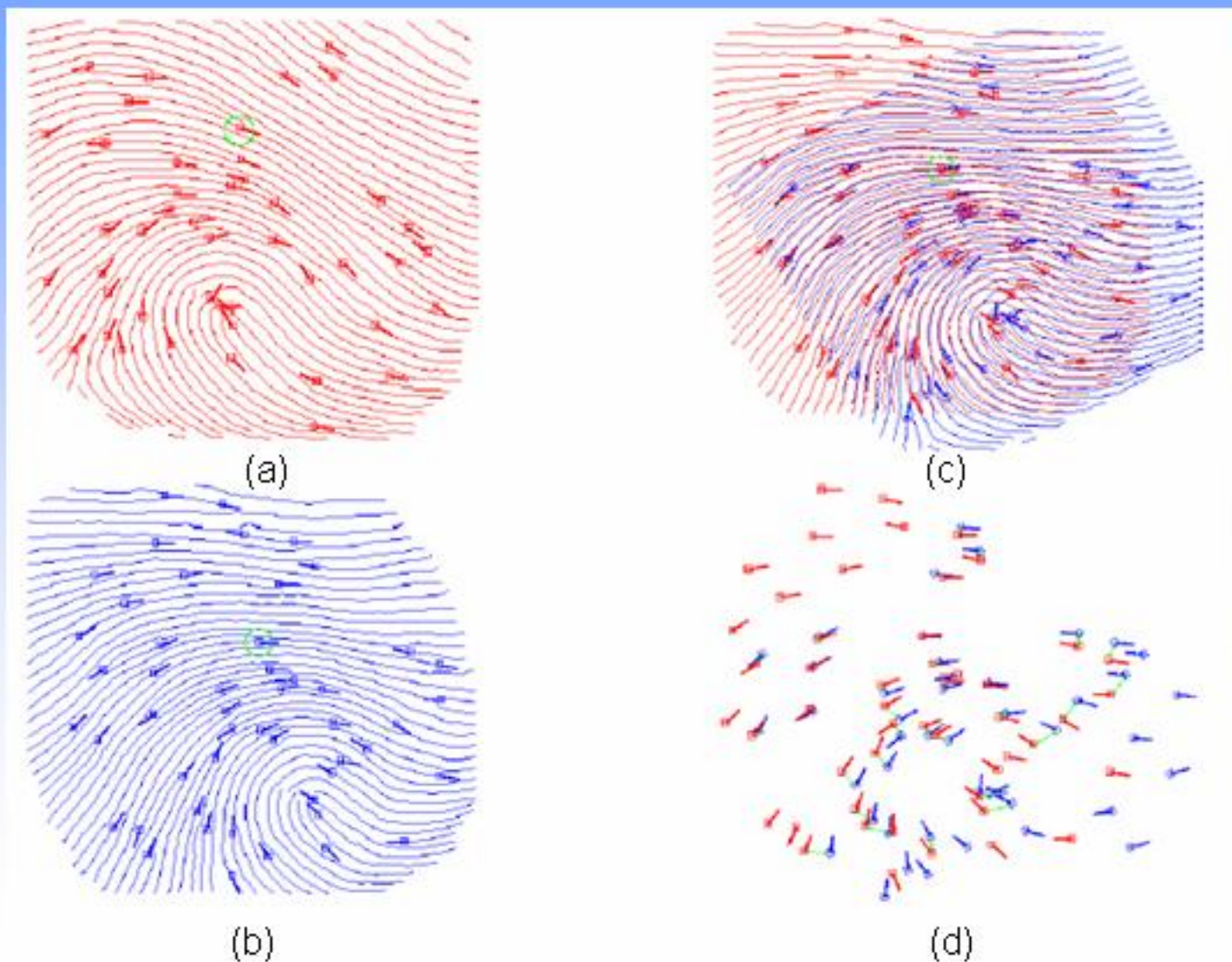


Matching Score

- The edit distance is used to establish the correspondence of the minutiae between P_p and Q_p
- Total number of corresponding minutiae is computed as M_{PQ}
- The matching score is

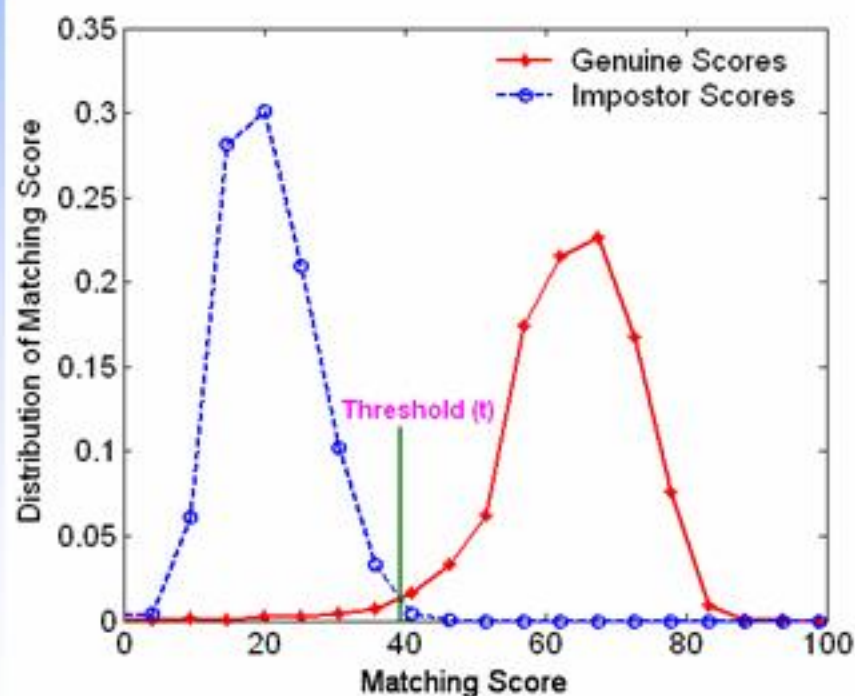
$$S = \frac{100M_{PQ}M_{PQ}}{MN}$$

Minutiae Matching Result

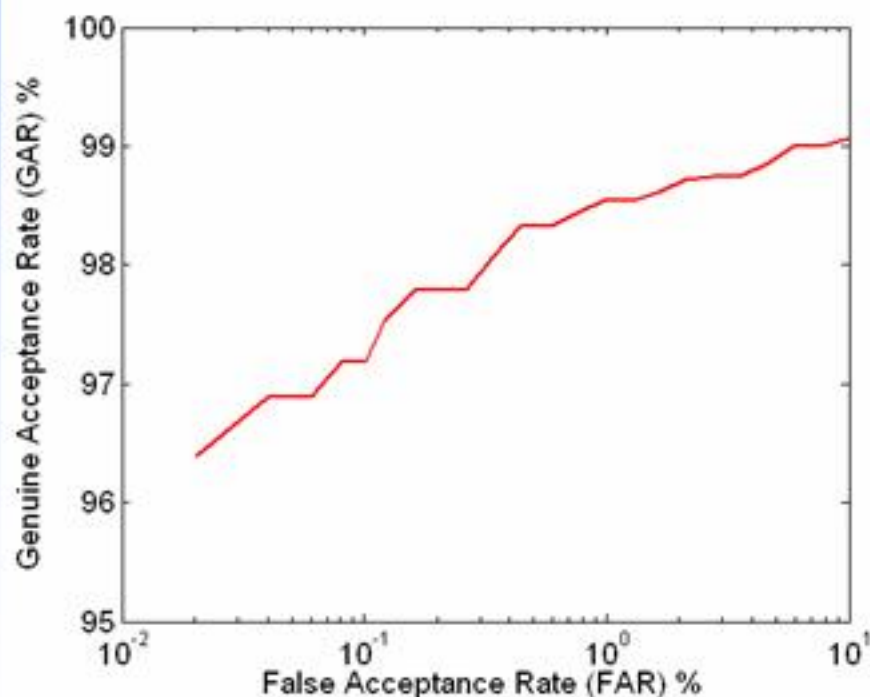


Matching Score Distributions

- Performance depends on the database. FVC2002 Database 1 (100 users, 8 impressions/user)
- For FAR = 0.1% (1 in 1000), GAR = 97.1%
- EER = 1.65%; at 0% False Accept, FRR = 4%

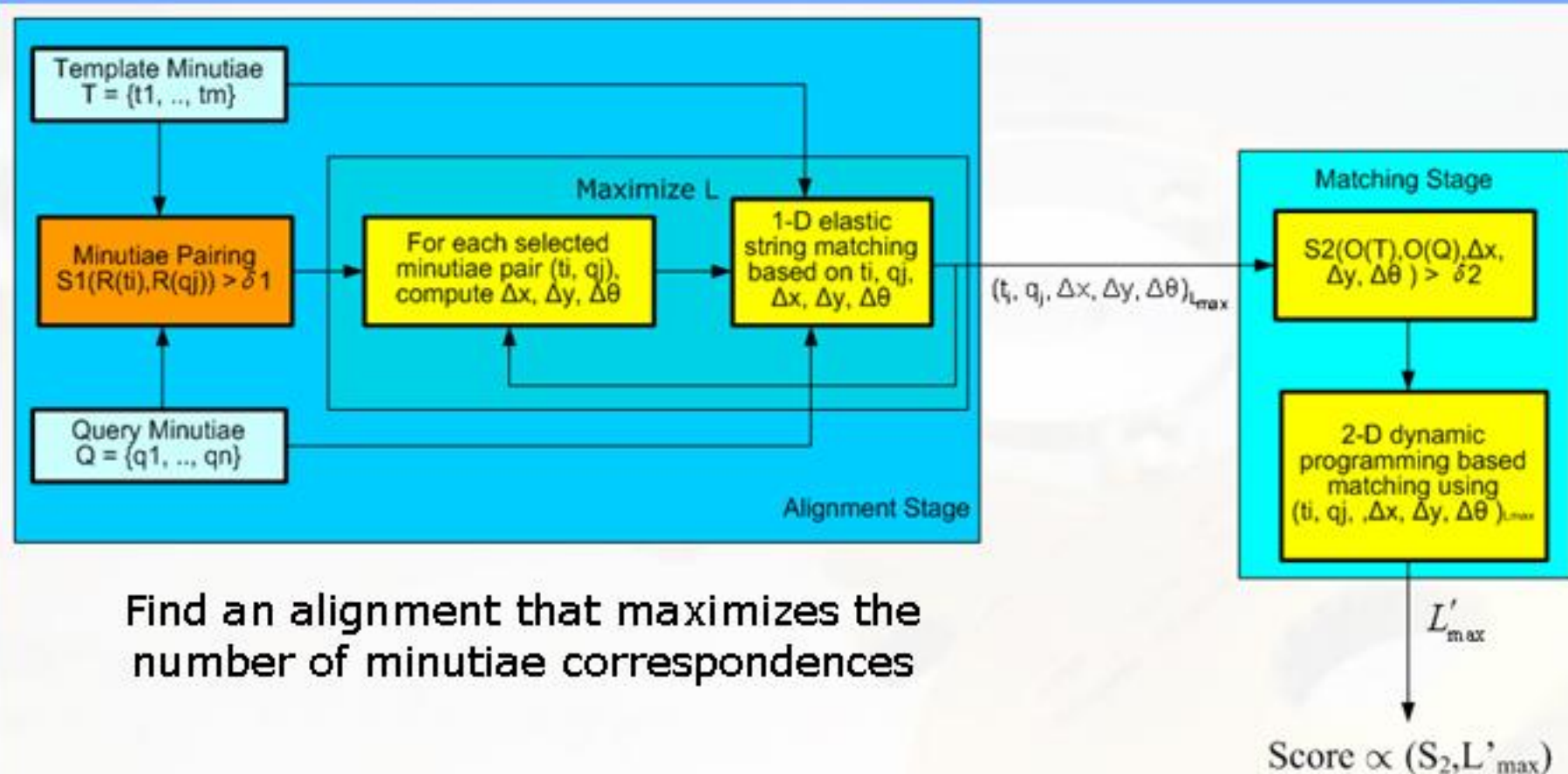


Matching Score Distribution



ROC Curve

2-D Dynamic Programming based Minutiae Matching



$S_1 \rightarrow$ Ridge similarity measure, $S_2 \rightarrow$ Orientation similarity measure,
 $R(t) \rightarrow$ 1-D representation of ridge points of minutia t , $O(T) \rightarrow$ Orientation field

Matching time ~ 0.1 sec.

Why is Fingerprint Matching Difficult?

- Translation
- Rotation
- Non-linear distortion
- Pressure & skin condition
- Sensor noise
- Feature extraction errors

Challenges in Fingerprint Identification

- Cuts and bruises on finger; dry or oily fingers; ~3% of fingerprints are not of "good" quality
- Wear and tear of sensor; no proven contactless fingerprint sensor technology is currently available
- New compact solid-state sensors capture only a small portion of the fingerprint
- Fingerprint impression is often left on the sensor
- Non-universality of fingerprint
- Changes in sensor technology; sensor interoperability



Fake fingerprint



Non-universality of fingerprint

Fingerprint Acquisition Process



Analysis of Errors

- Minutiae Extraction

- Extraction stage does not extract all minutiae and their ridges
- There may be no corresponding minutiae having ridge points for finding the correct alignment

- Alignment

- Corresponding minutiae with ridge points exist
- Alignment step fails due to small number of correspondences

- Matching

- Estimated alignment is correct
- But, the matching score is low because the number of correspondences is low compared to the number of minutiae
- Reasons: deformation, spurious and missing minutiae

Minutiae Extraction Failure

A



B



True Minutiae Matches: $A1 \rightarrow B3$, $A18 \rightarrow B9$, $A19 \rightarrow B7$

A1, B9 and B7 were detected, but the associated ridges were not detected because they are close to the boundary

Alignment Failure

A



B

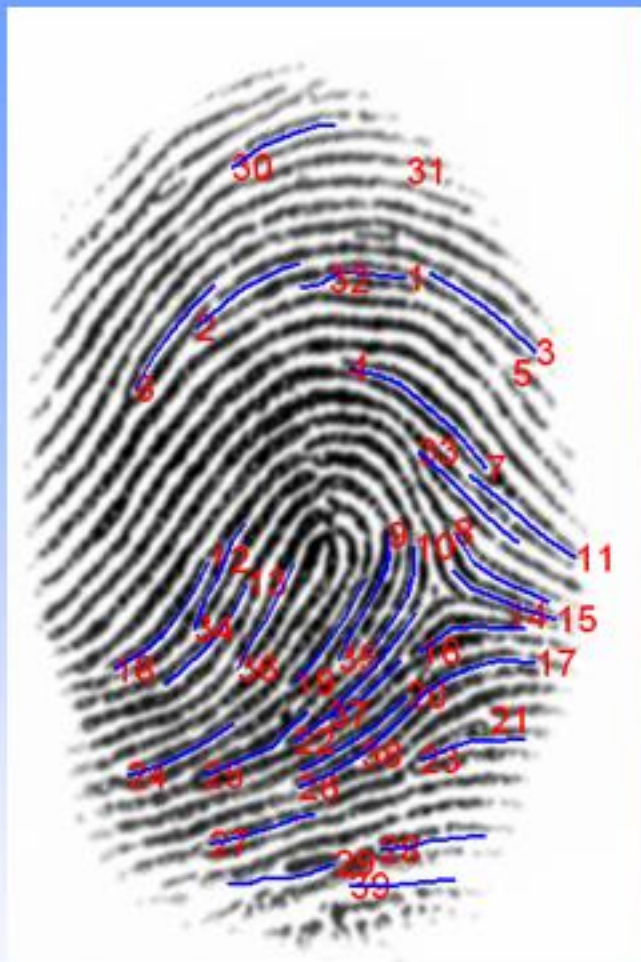


True Minutiae Matches: A7→B9, A8→B8, A4→B1

A7→B9 and A8→B8 pairs have ridge points; however, there exists a false alignment that results in more than three matches

Matching Failure

A



B



No. of matching minutiae identified by the matcher = 10

No. of minutiae in A = 38; No. of minutiae in B = 34

Spurious minutiae and large deformation leads to small score

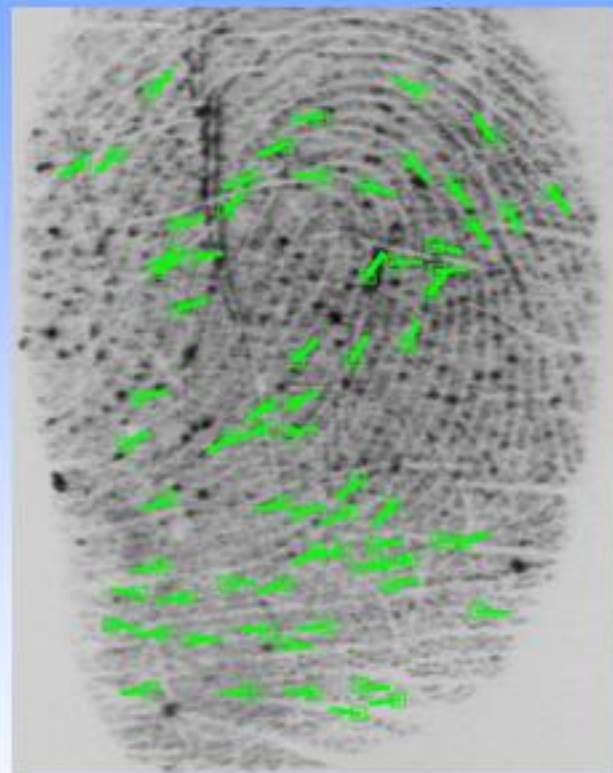
Noisy Images



Quality Index = 0.96
False Minutiae=0

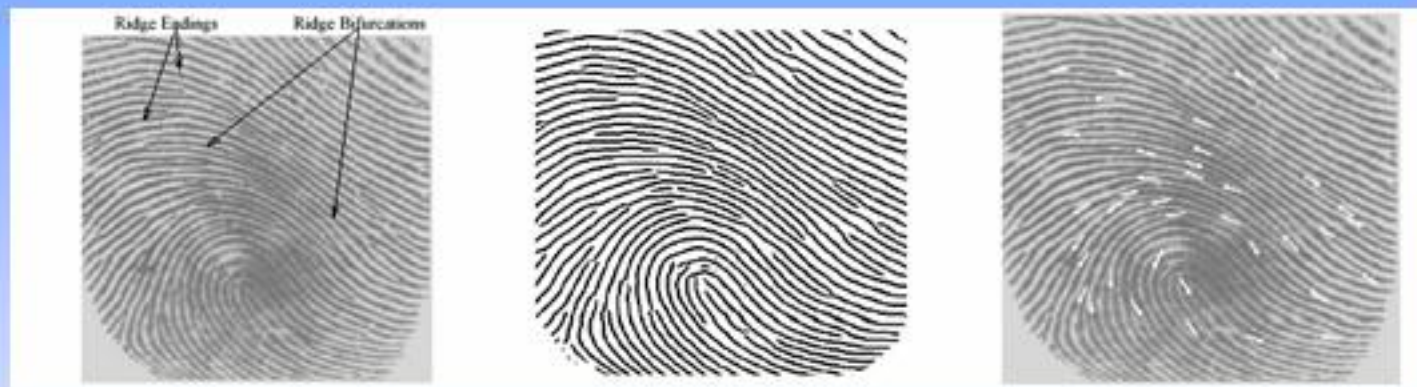


Quality Index = 0.53
False Minutiae=7



Quality Index = 0.04
False Minutiae=27

Motivation for Fingerprint Enhancement

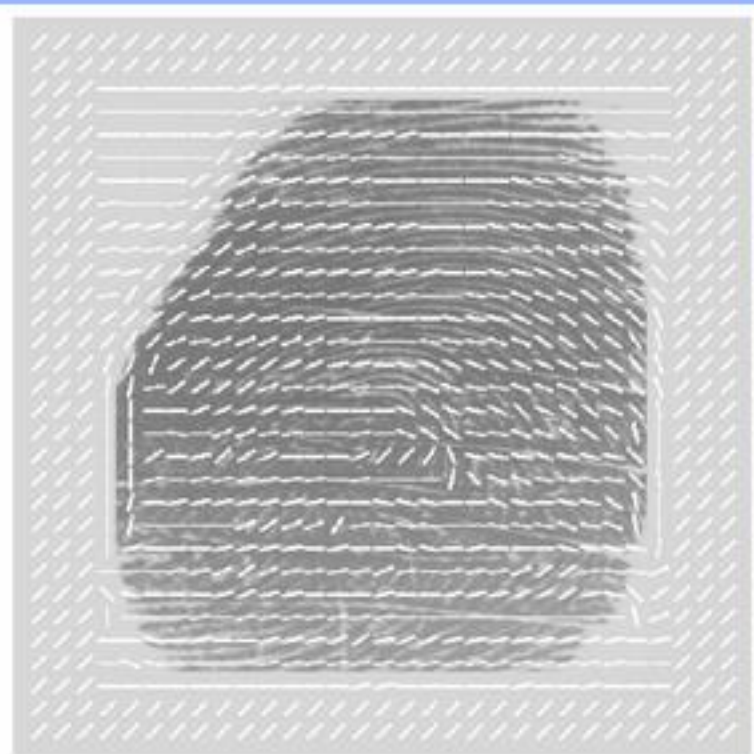
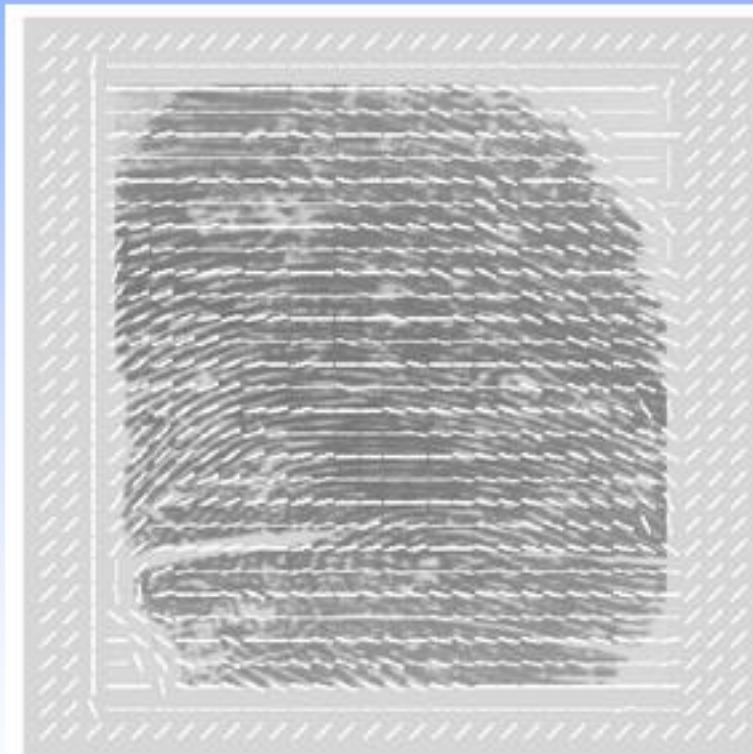


Minutia extracted from a good quality input image

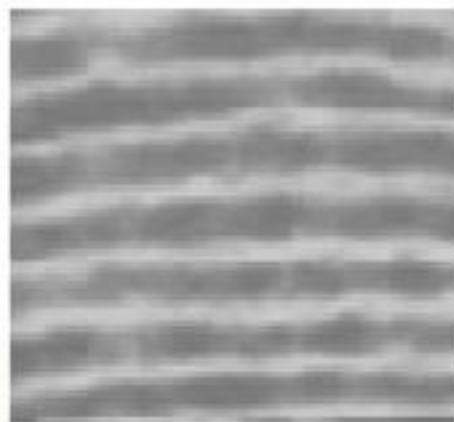


Minutia extracted from a poor quality input image

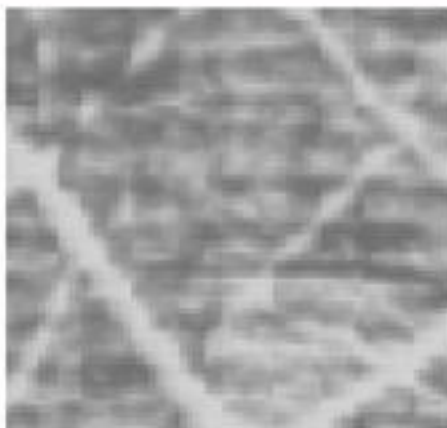
Difficulty in Orientation Field Estimation



Fingerprint Regions



Well defined region



Recoverable
corrupted region



Unrecoverable
corrupted region

Fingerprint Enhancement Algorithm

- A bank of even-symmetric Gabor filters is applied to the fingerprint image
- A ridge extraction algorithm is applied to each of the filtered images and the corresponding ridge map is obtained
- A voting algorithm is used to generate a coarse-level ridge map and the unrecoverable region masks
- Orientation field estimation is applied to the coarse-level ridge map and from the computed orientation field enhanced images are obtained

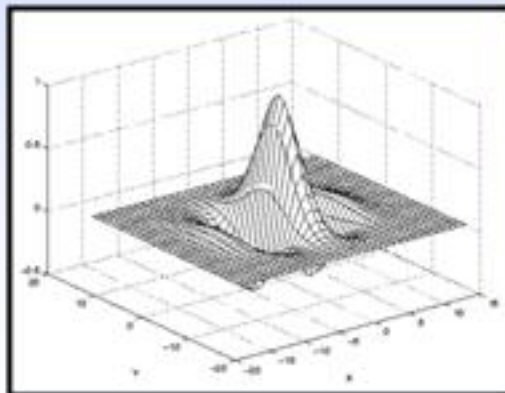
Fingerprint Enhancement Algorithm

- Gabor filters are both frequency and orientation selective
- A Gabor filter with the correct **local orientation** and **local frequency** can remove noise while preserving the true ridges
- The algorithm is computationally intensive and therefore applied only to the template image
- A fast enhancement algorithm is applied to the input images during live verification

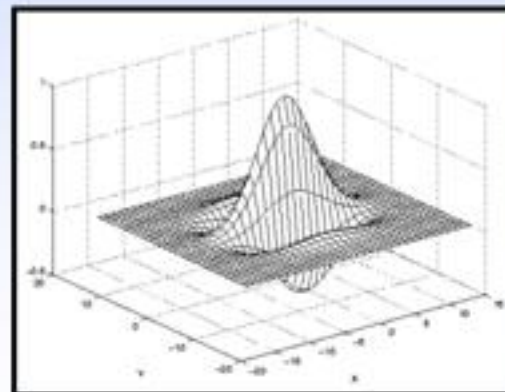
Even-symmetric Gabor Filters

$$G_{\theta,f}(x,y) = \exp\left\{\frac{-1}{2}\left[\frac{x'^2}{\delta_x^2} + \frac{y'^2}{\delta_y^2}\right]\right\} \cos(2\pi f x'),$$
$$x' = x \sin\theta + y \cos\theta,$$
$$y' = x \cos\theta - y \sin\theta,$$

where f is the frequency of the sinusoidal plane wave at an angle θ with the x -axis, and δ_x and δ_y are the standard deviations of the Gaussian envelope along the x and y axes, respectively.



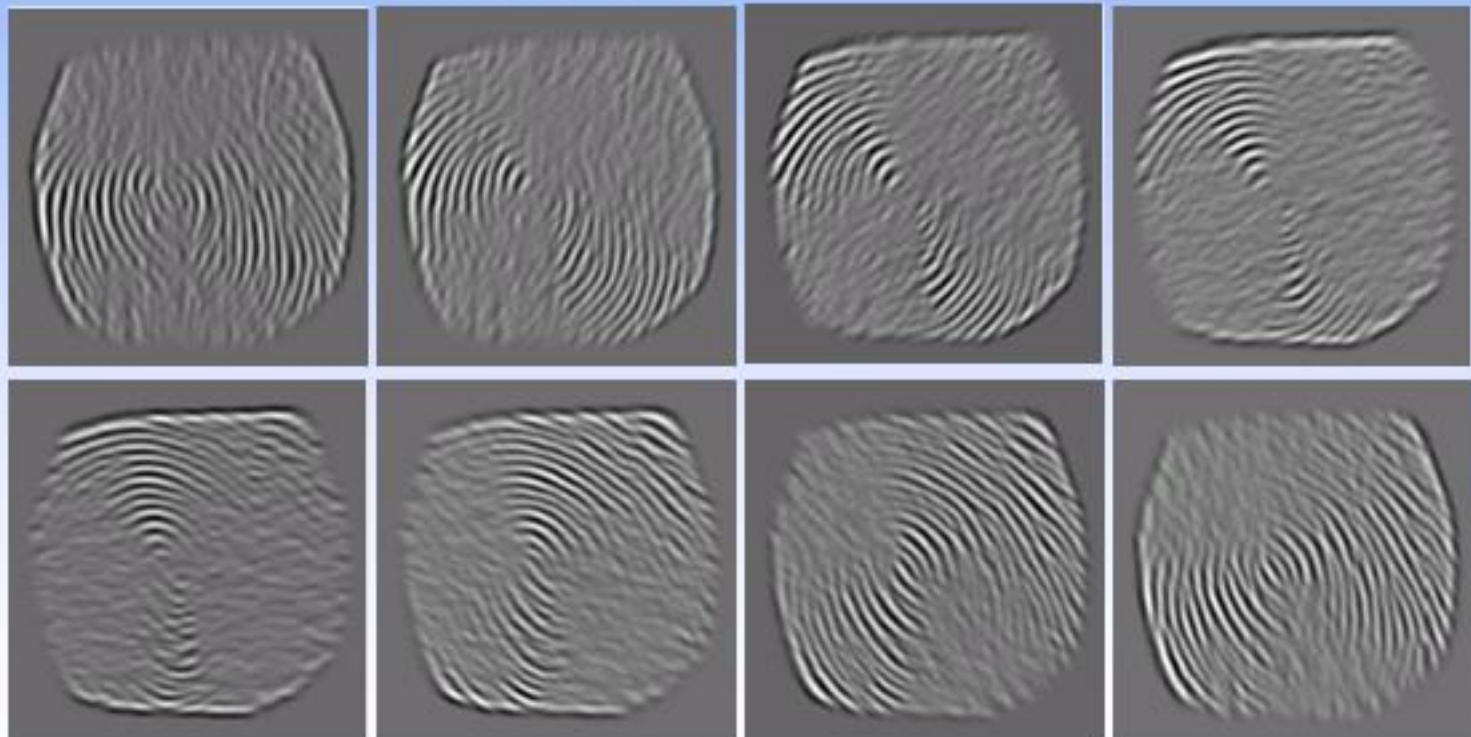
0° orientation filter



45° orientation filter

Filtered Images

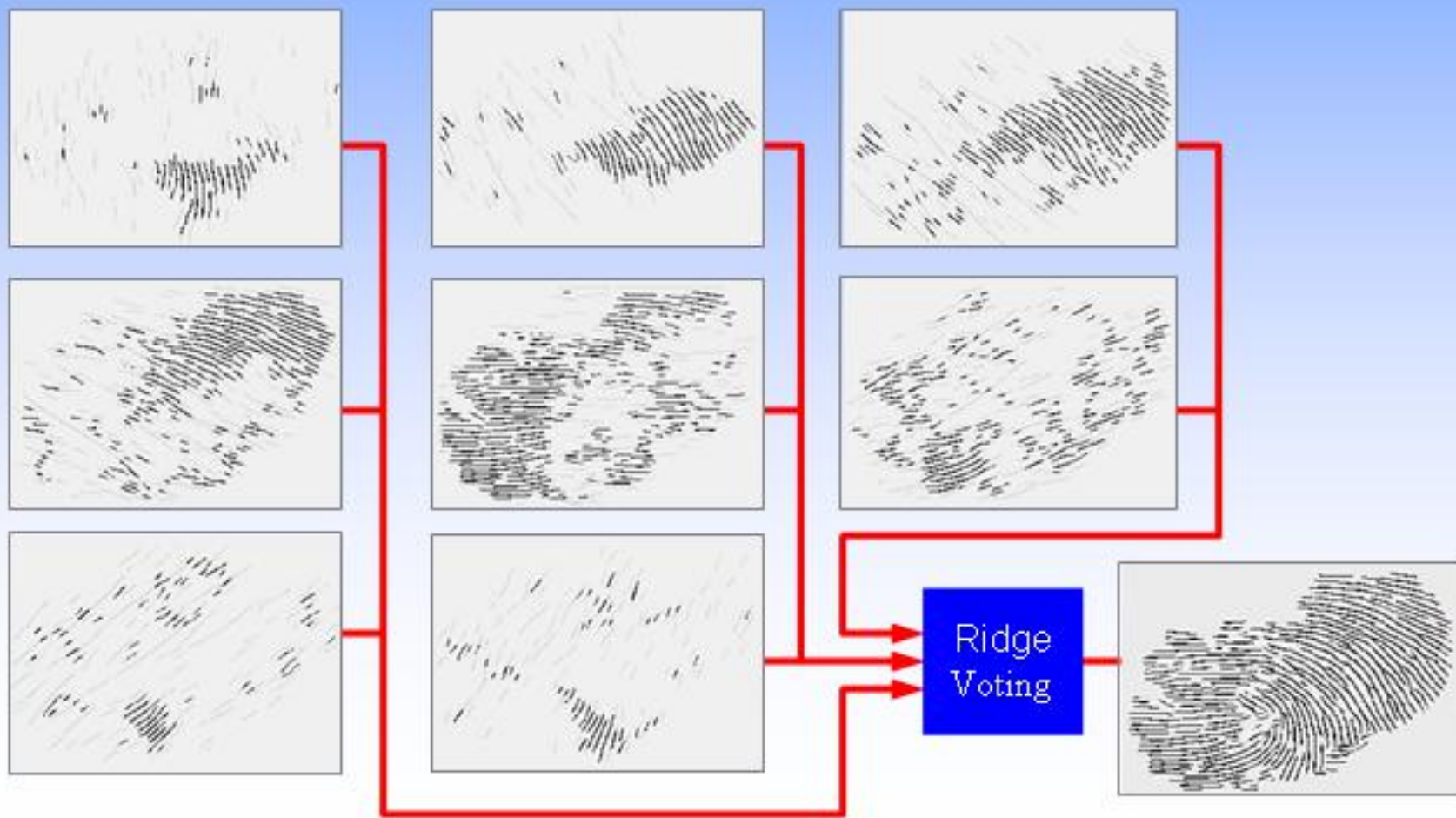
- An input fingerprint image is filtered using 8 Gabor filters all having the same frequency but different orientations (0° , 22.5° , 45° , 67.5° , 90° , 112.5° , 135° , 157.5°)



Fingerprint Enhancement



A set of 8 Gabor filters with different orientations is used



Results of Enhancement



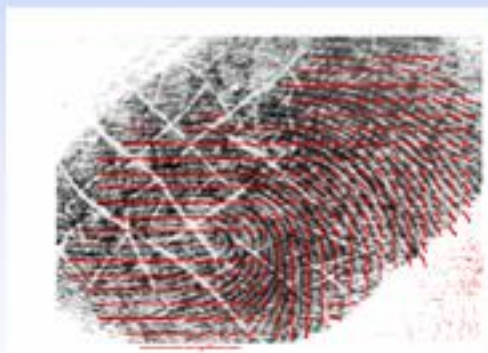
Input image



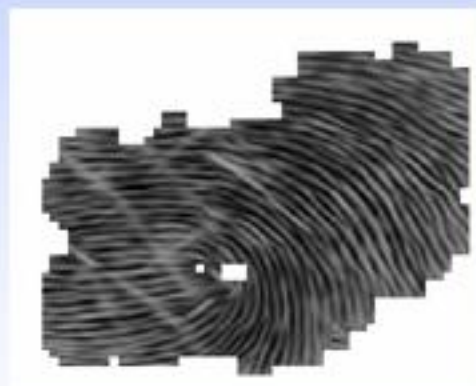
Coarse ridge map



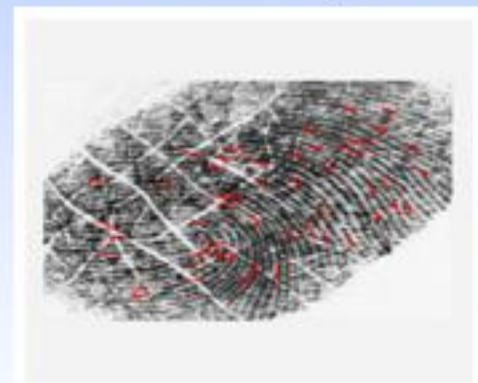
Unrecoverable region mask



Estimated orientation field

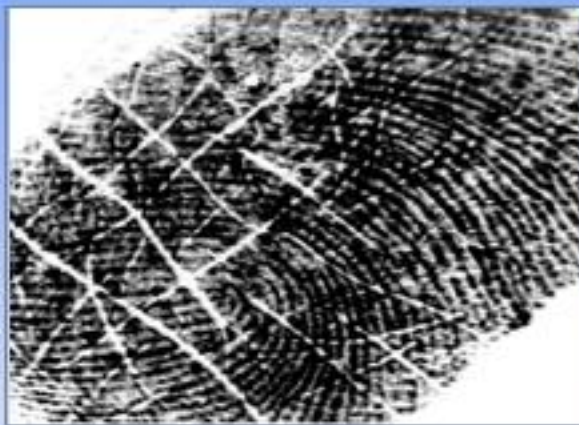


Enhanced image



Extracted minutiae

Fingerprint Enhancement

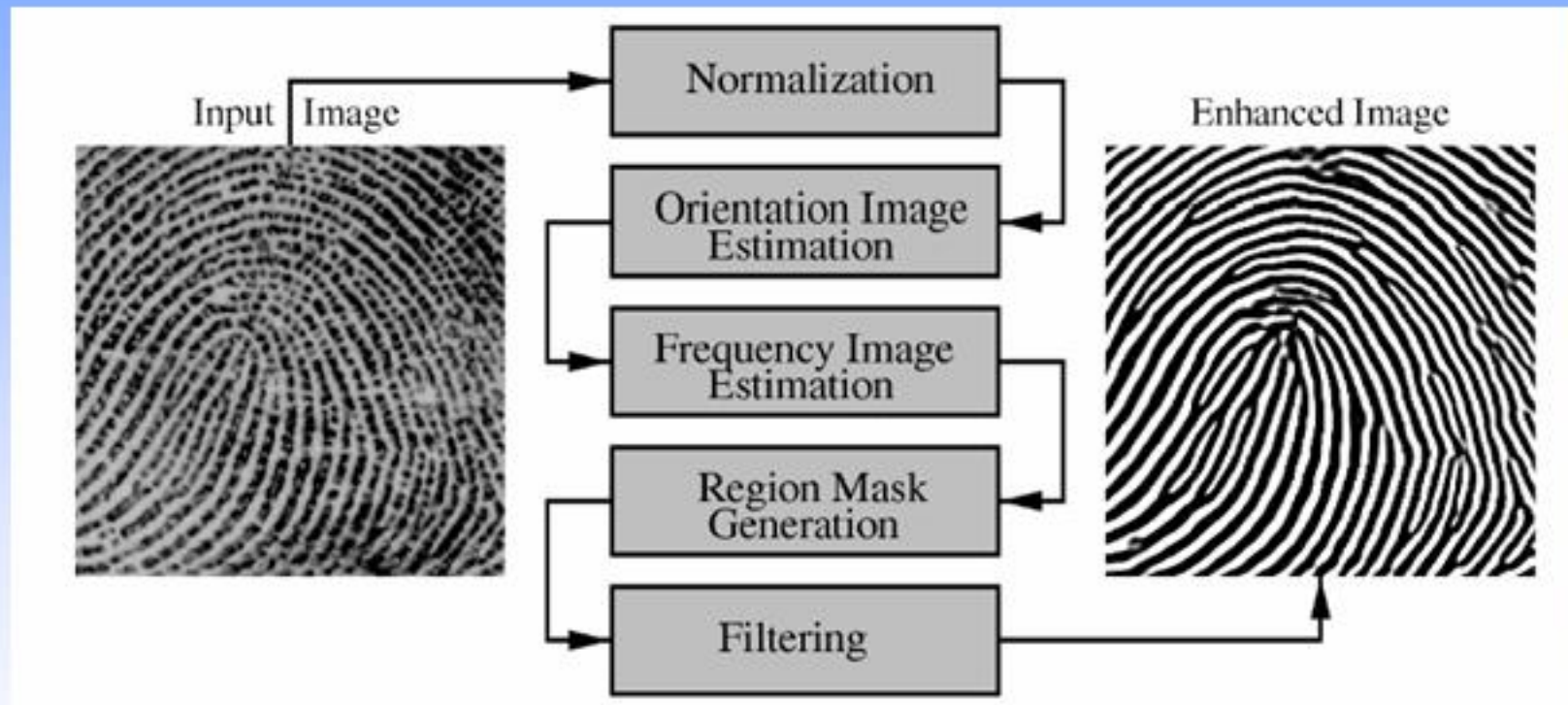


Minutiae extraction before enhancement

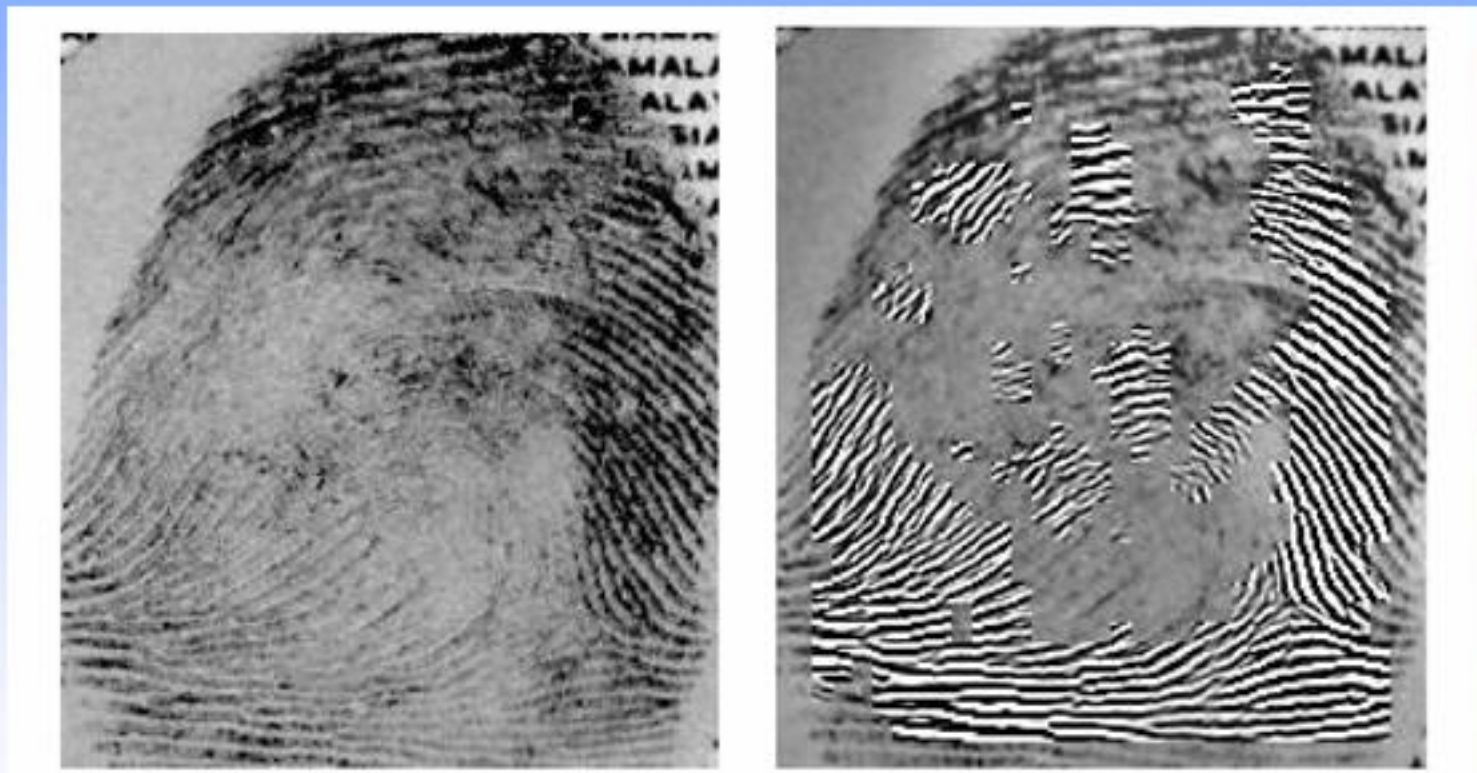


Minutiae extraction after enhancement

Fast Enhancement Algorithm

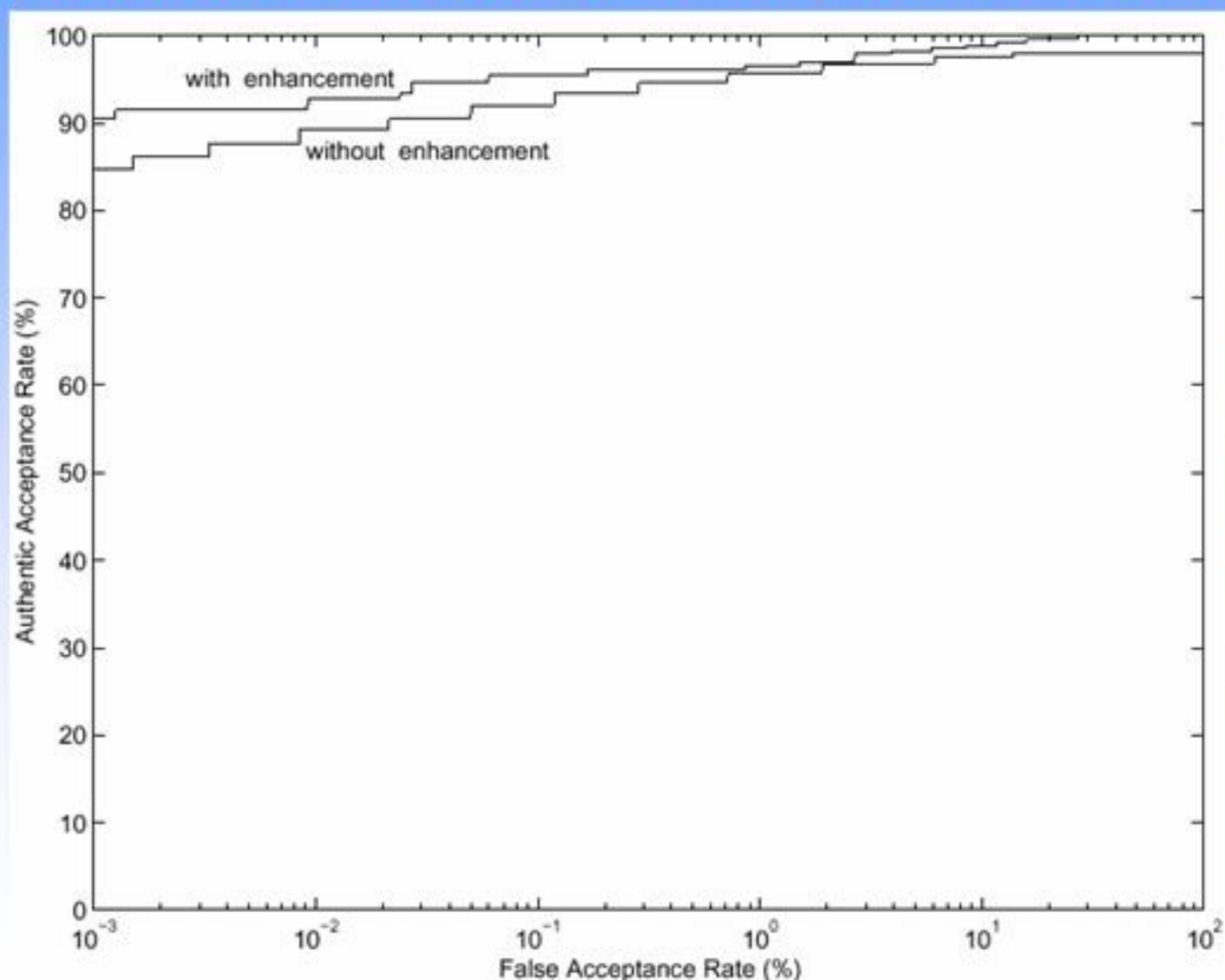


Results of Fast Enhancement Algorithm

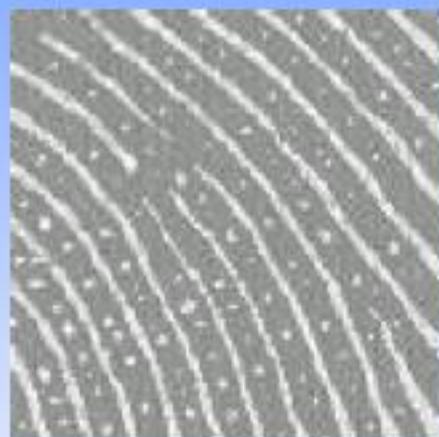


Performance with Enhancement

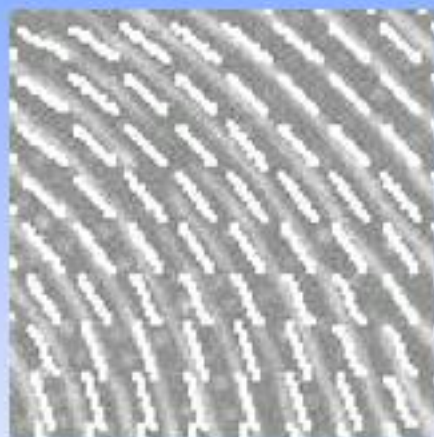
Quantitative evaluation of enhancement module



Fingerprint as Oriented Texture



(a) Ridges in local region



(b) Ridge directions in (a)



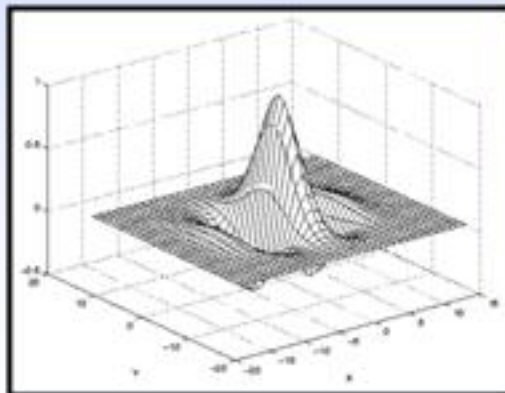
(c) Fourier spectrum of (a)

The ridge pattern in a fingerprint may be viewed as an **oriented texture pattern** having a fixed dominant spatial frequency and orientation in a local neighborhood. The frequency is due to the inter-ridge spacing present in the fingerprint and the orientation is due to the ridge flow pattern

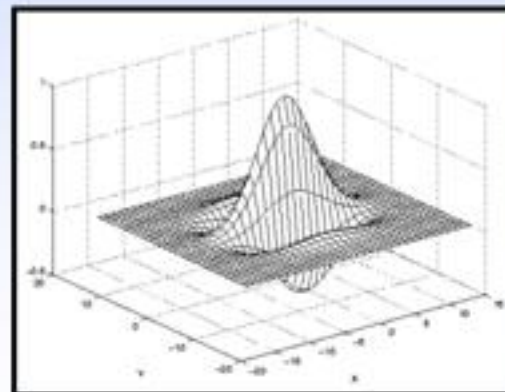
Even-symmetric Gabor Filters

$$G_{\theta,f}(x,y) = \exp\left\{\frac{-1}{2}\left[\frac{x'^2}{\delta_x^2} + \frac{y'^2}{\delta_y^2}\right]\right\} \cos(2\pi f x'),$$
$$x' = x \sin\theta + y \cos\theta,$$
$$y' = x \cos\theta - y \sin\theta,$$

where f is the frequency of the sinusoidal plane wave at an angle θ with the x -axis, and δ_x and δ_y are the standard deviations of the Gaussian envelope along the x and y axes, respectively.



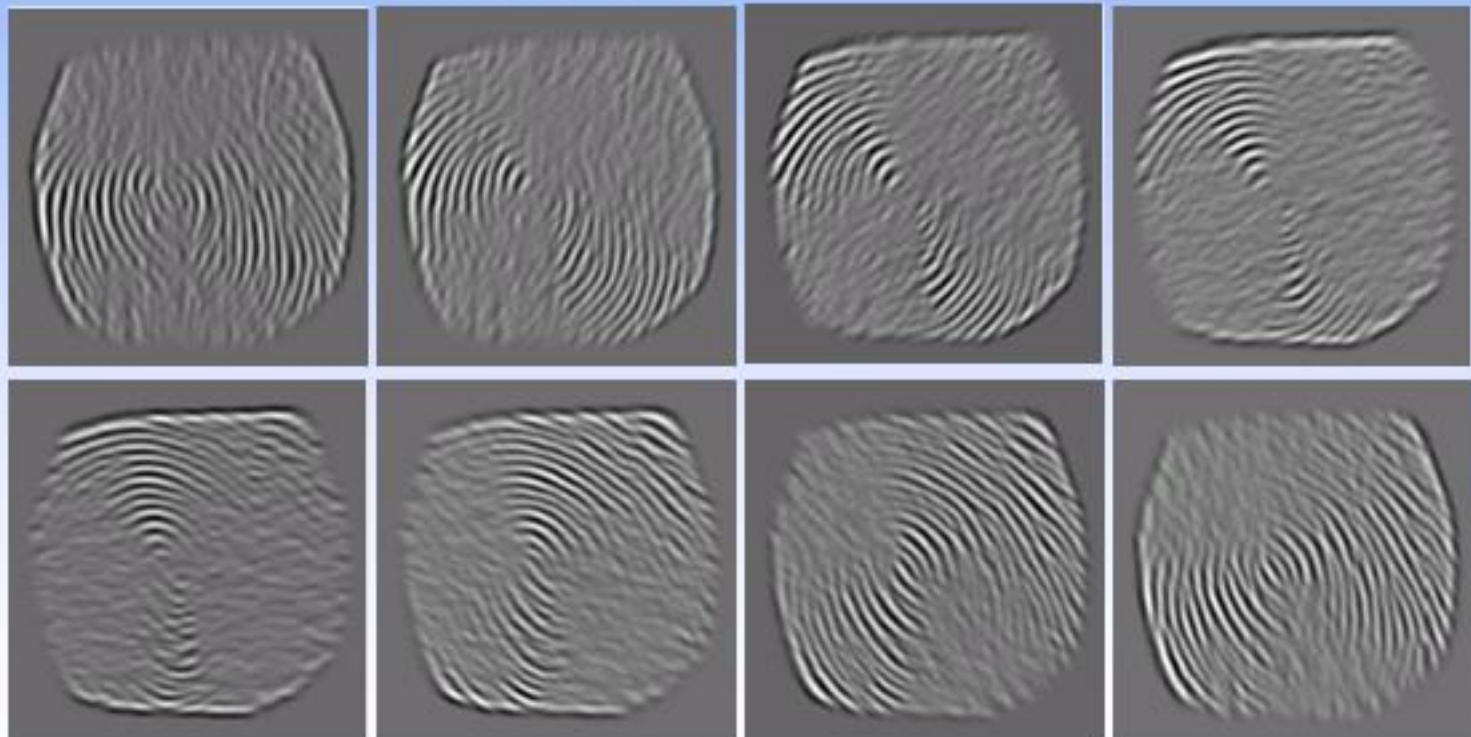
0° orientation filter



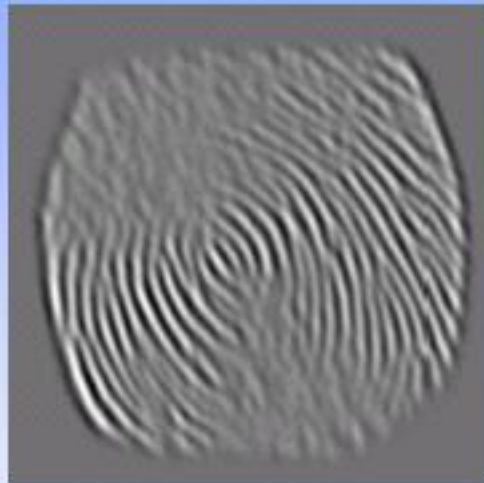
45° orientation filter

Filtered Images

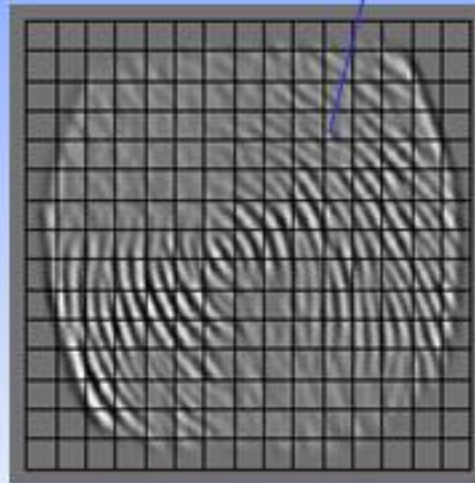
- An input fingerprint image is filtered using 8 Gabor filters all having the same frequency but different orientations (0° , 22.5° , 45° , 67.5° , 90° , 112.5° , 135° , 157.5°)



Texture-based Representation

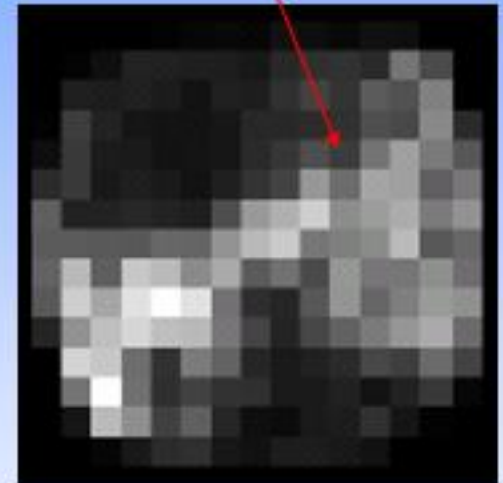


(a) Filtered image



(b) Square tessellation

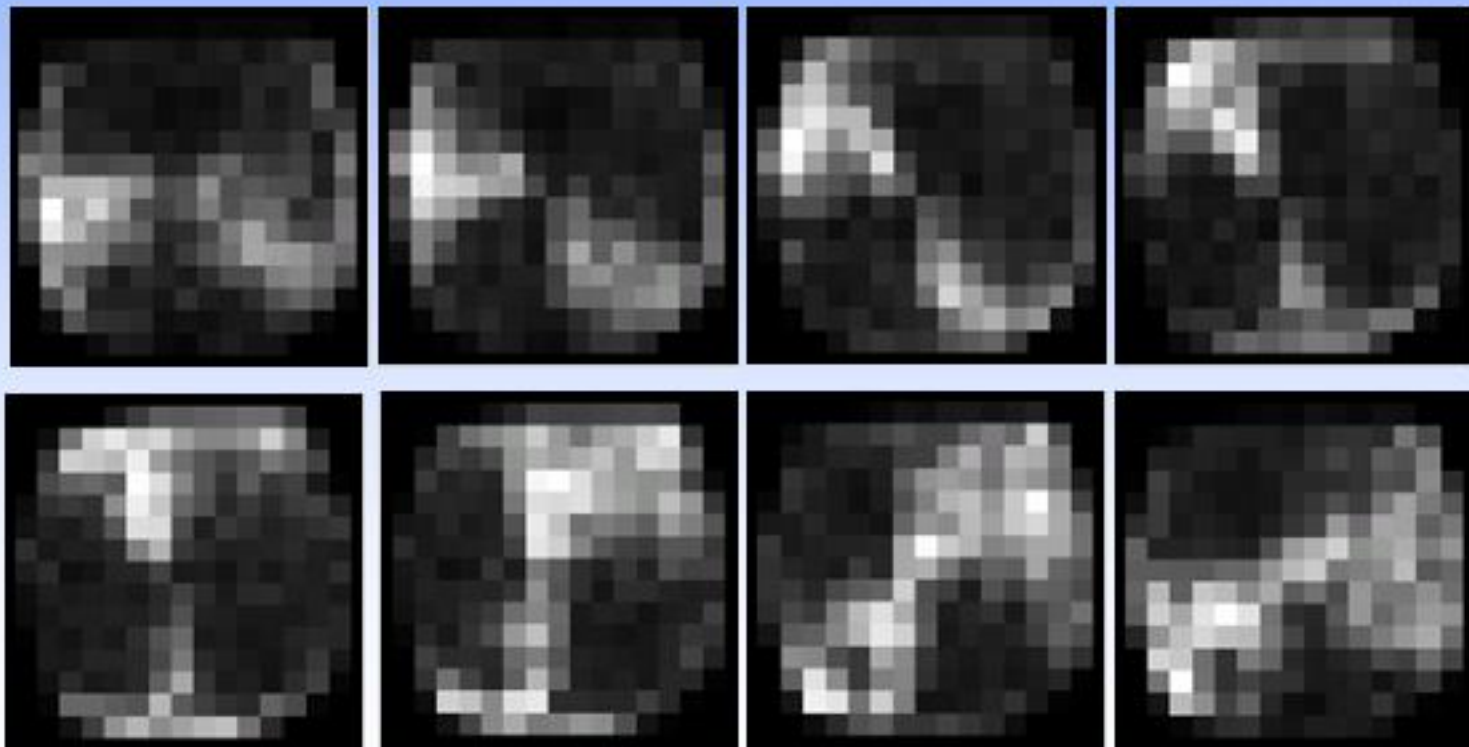
Compute variance of
each cell



(c) Feature values

Ridge Feature Map

- The filtered images are examined using a square tessellation and the variance of pixel intensities in every cell is used as a feature value

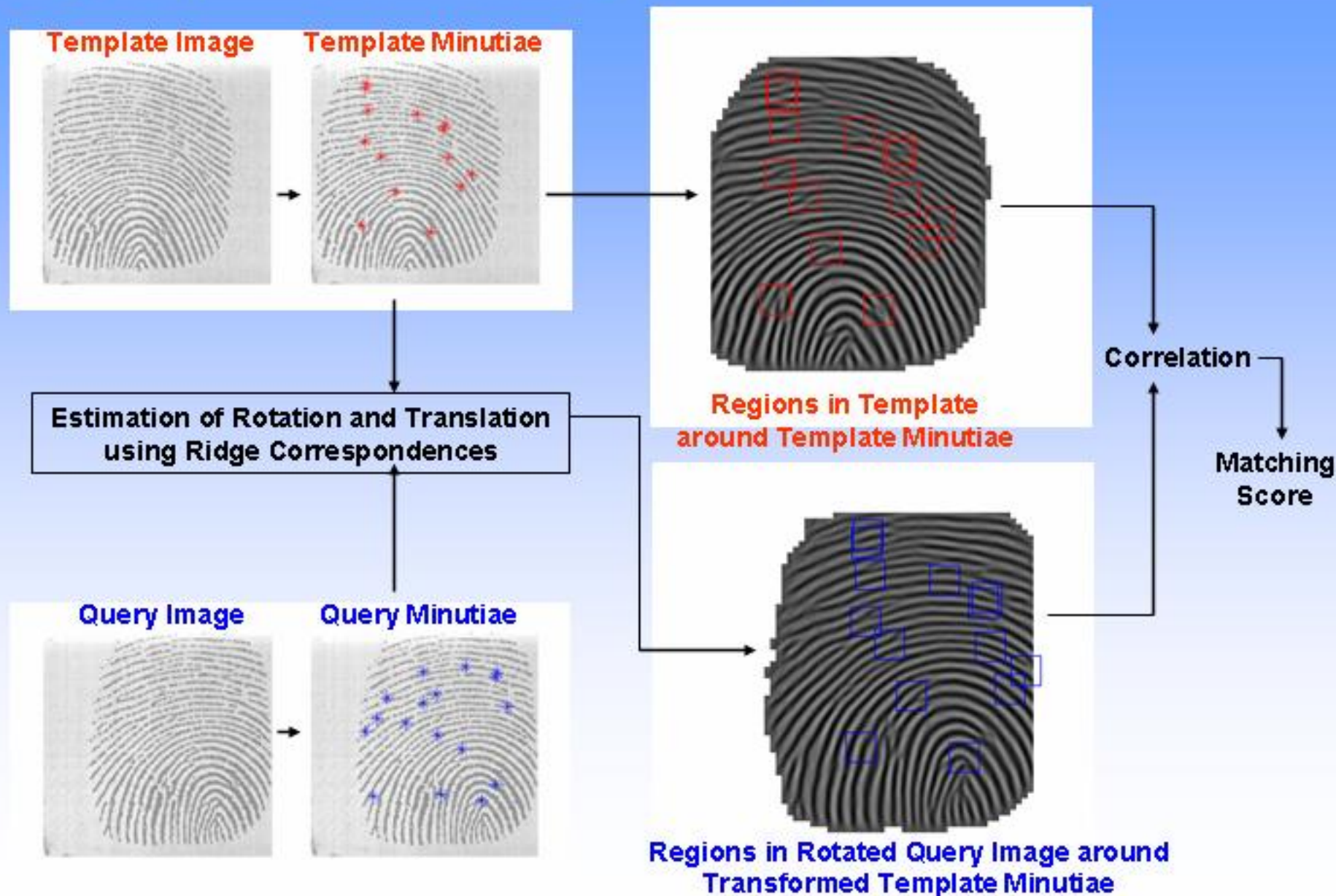


The ridge feature map is a fixed-length feature vector

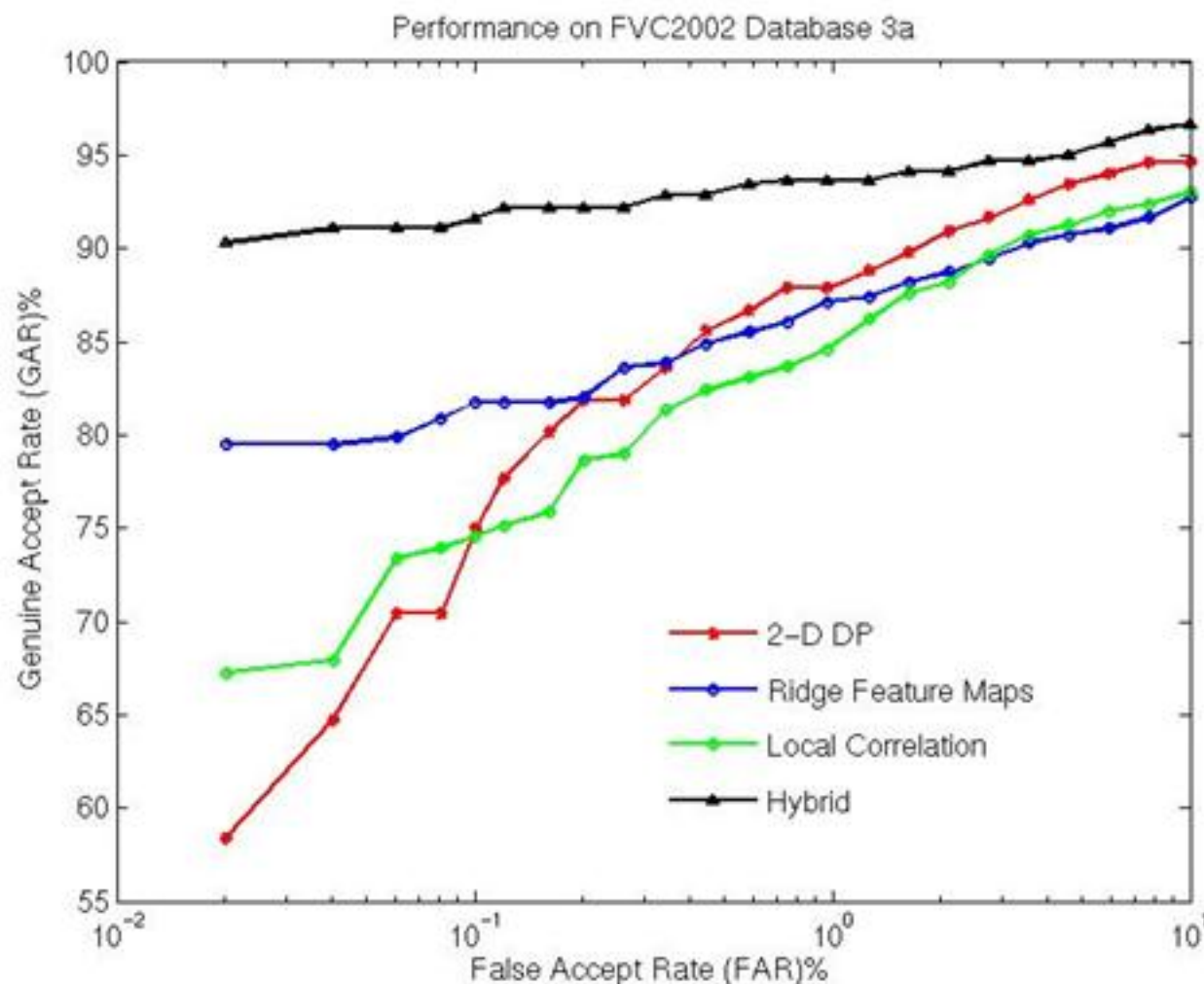
Correlation-based Matching Algorithm

- Normalized cross-correlation of regions around corresponding minutia points is used to describe the quality of a minutia match
- Gray level values around the minutiae retain most of the local information; hence, this method determines the degree of minutia match accurately
- Procrustes analysis of corresponding ridge curves is used to estimate rotations and displacements
- Gabor filter-bank based technique is used for fingerprint enhancement and segmentation
- Since correlation is done locally, the method is reasonably resistant to non-linear deformations

Fingerprint Matching using Local Correlation

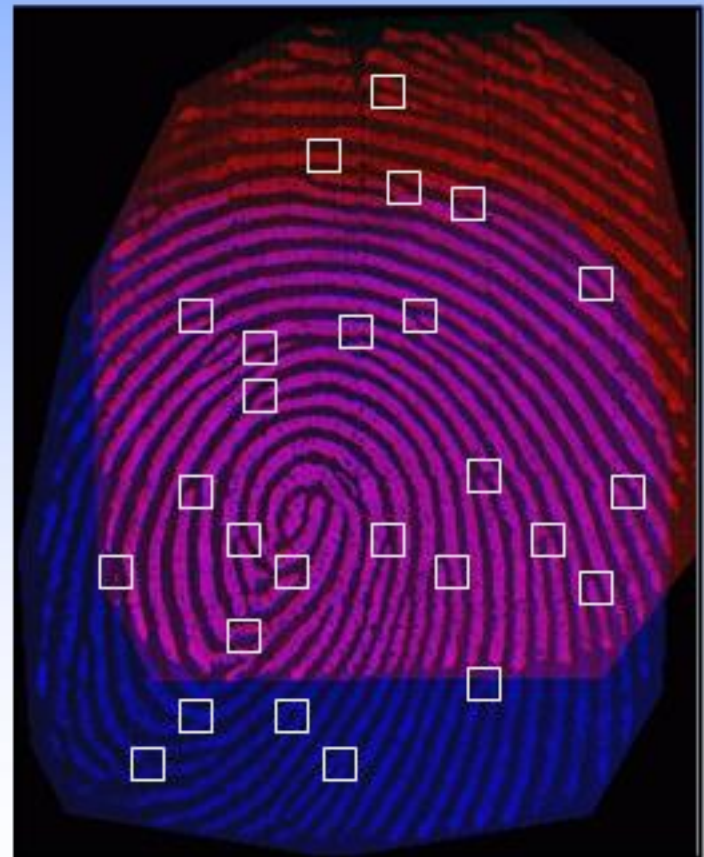
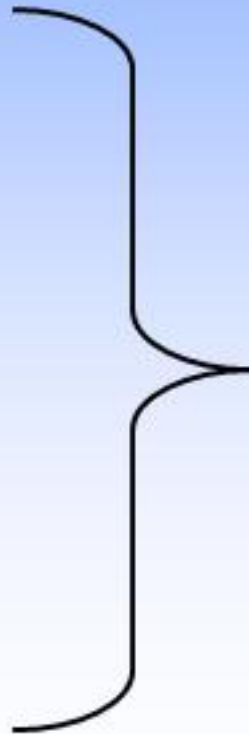
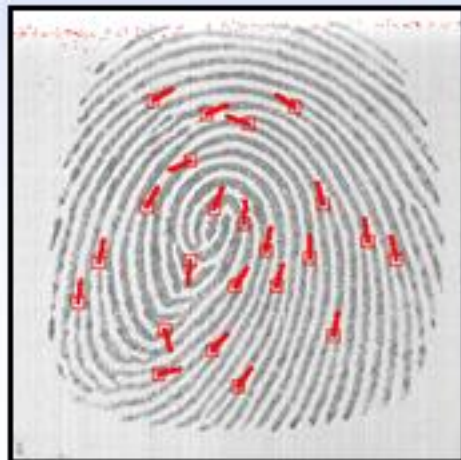


Performance of Hybrid Matcher (Minutiae, Texture & Local Correlation)



Fingerprint Mosaicking

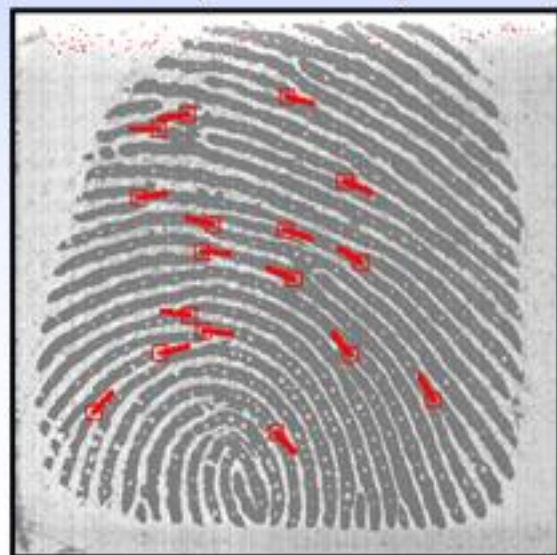
Stitching two fingerprint impressions of a user to create a composite template comprising of more number of minutiae points and more texture information



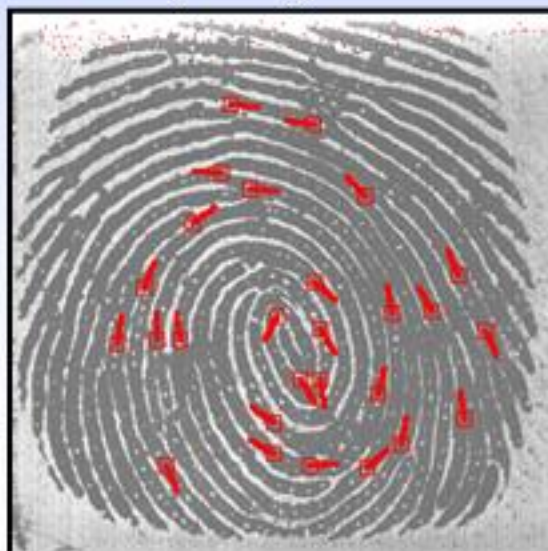
Motivation for Mosaicking

- Solid state fingerprint sensors are small & capture only a limited portion of a fingerprint
- Multiple impressions of the same finger may have small overlap. Consequently, fewer minutiae points available for matching. Results in degraded performance of the fingerprint matcher

Template Image

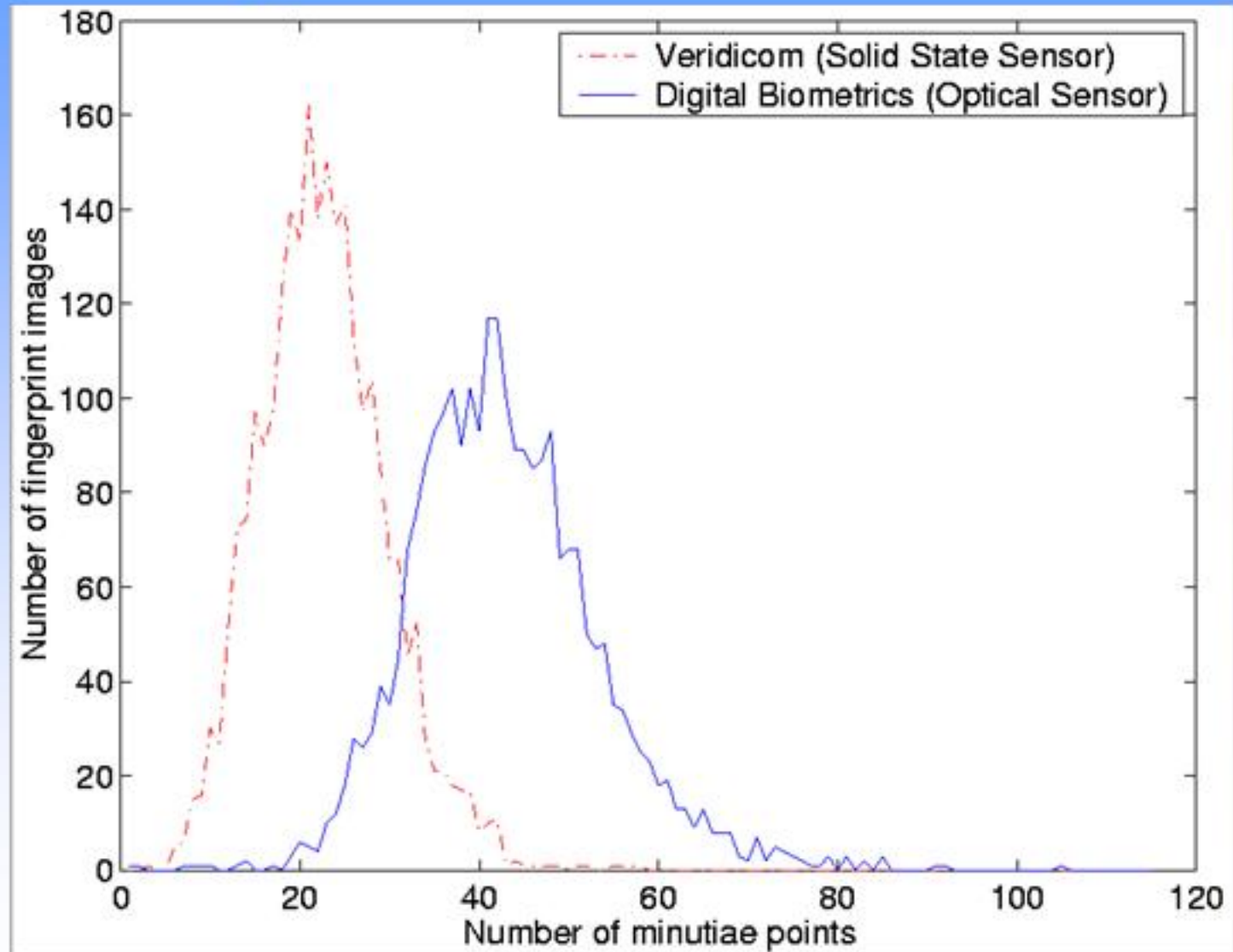


Query Image



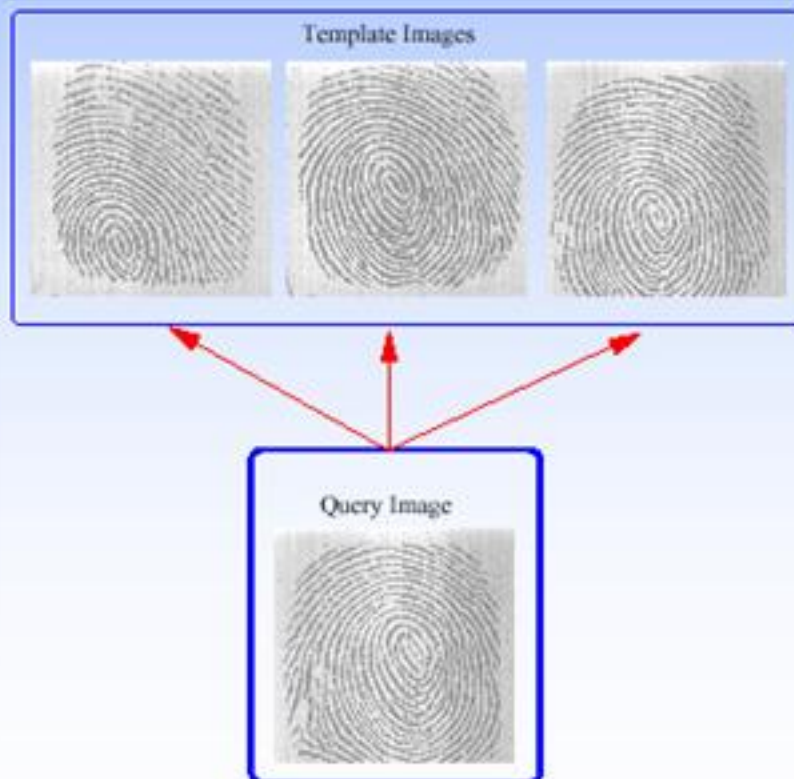
Two images of the same finger having very few common minutiae points

Histogram of Minutiae Points



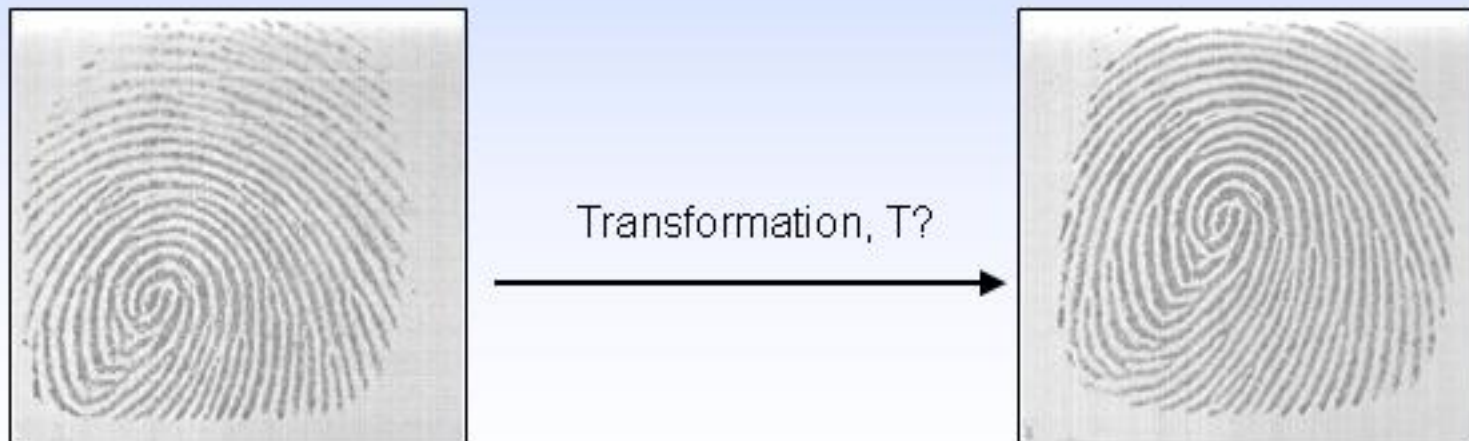
Advantages of Mosaicking

- Reduces storage and matching time
- Improves integrity of matching
- Resolves problem of template selection



Problem Description

- Given two impressions of the same finger, find a global transformation, T , that relates the two images
- Use global transformation to generate composite template



Difficulty in mosaicking

- Non-linear distortions due to pressing a convex elastic surface (finger) on a flat surface (sensor)
- Noisy images due to dirt deposits



Two different impressions of the same finger using a Digital Biometrics scanner.

Mosaicking Algorithm

- Given: two fingerprint images, I_P and I_Q , of size $M \times M$; $I_p(x,y)$ denotes the intensity at (x,y) , $x,y=1..M$
- Compute range images, R_P and R_Q ; $R_p=\{(x,y,I_p(x,y))\}$, $x,y=1,..M$
- Align R_P with R_Q using the iterative closest point (ICP) surface registration algorithm
- Initial 3D affine transformation, T^0 , for the ICP algorithm is provided by minutiae points extracted from I_P and I_Q

$$T = \begin{bmatrix} \cos \alpha \cos \beta & \cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma & \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma & t_x \\ \sin \alpha \cos \beta & \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & t_y \\ -\sin \beta & \cos \beta \sin \gamma & \cos \beta \cos \gamma & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

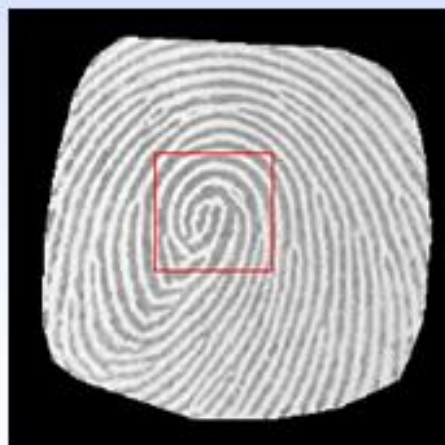
Fingerprint as a Range Image



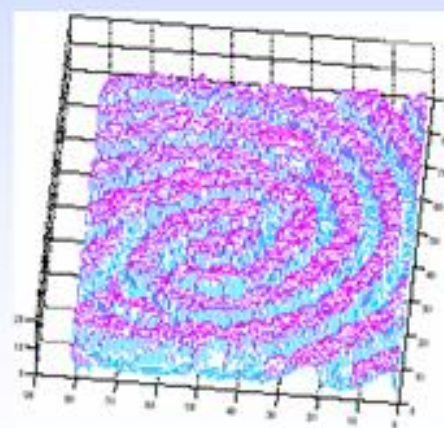
(a) Input Image



(b) Median filtered Image



(c) Segmented Image



(d) Range image

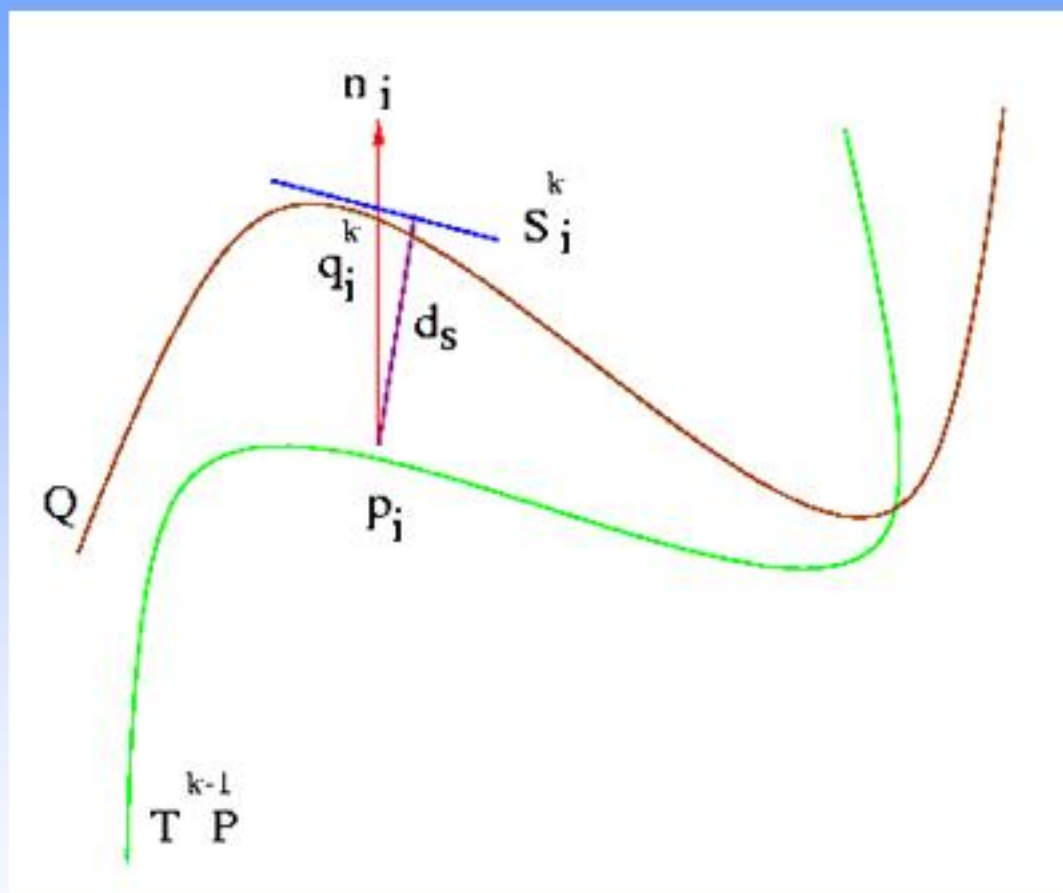
The ICP Algorithm*

ICP minimizes distance from a point to a plane

1. Let $\{p_i\}$, $p_i \in R_P$, be a set of control points, $i=1..N$, and let $\{n_i\}$ be the surface normal at these points
2. Do for $k=1,2,3...$ until $|e^k - e^{k-1}| / N \leq \varepsilon$
 - a) For every p_i
 - i. Apply T^{k-1} to p_i and n_i and obtain p_i' and n_i'
 - ii. Find $q_i^k \in R_Q$ which intersects with the normal line defined by p_i' and n_i'
 - iii. Compute tangent plane S_i^k of R_Q at q_i^k
 - b) Find T that minimizes $e^k = \sum_{i=1}^N d_s(T \otimes T^{k-1} p_i, S_i^k)$
 - c) Let $T^k = T \otimes T^{k-1}$

* Chen and Medioni, "Object Modeling by Registration of Multiple Range Images", *Image and Vision Computing*, Vol. 10, No. 3, April 1992

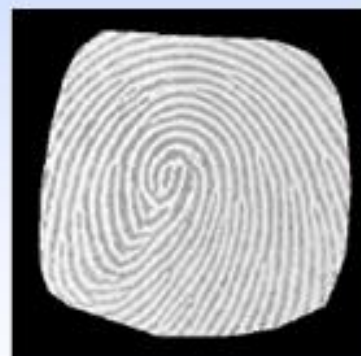
The ICP Algorithm



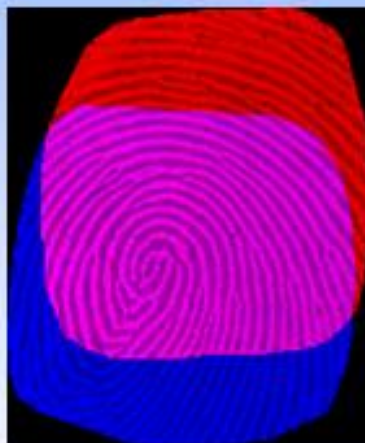
Composite Templates



First image



Second image



Aligning the images



Extract minutiae from
mosaicked image

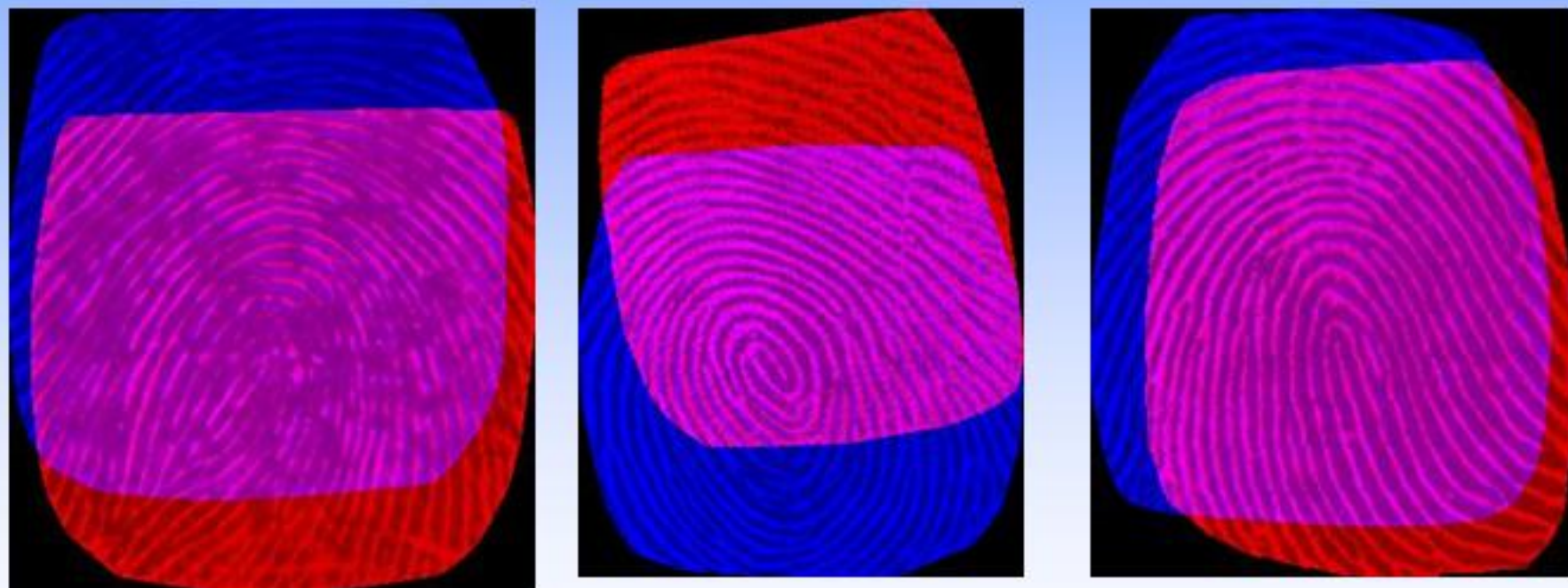


Augment minutiae set using
transformation matrix

Average number of minutiae

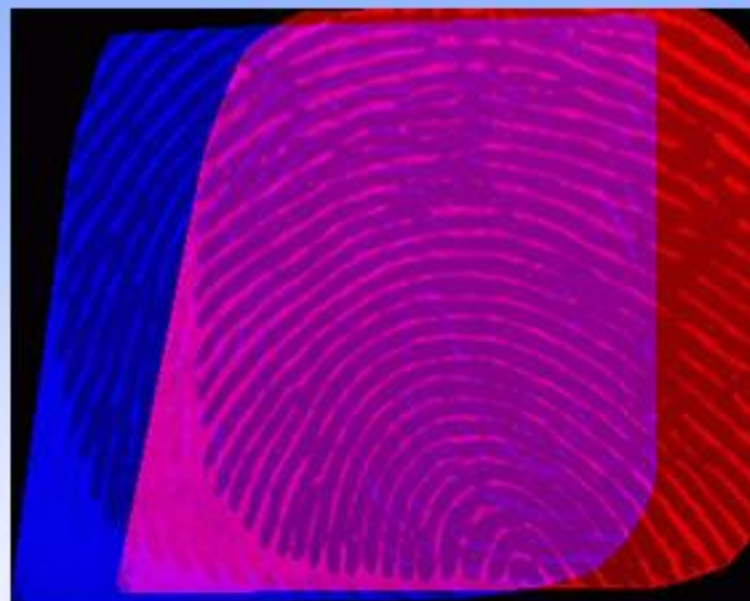
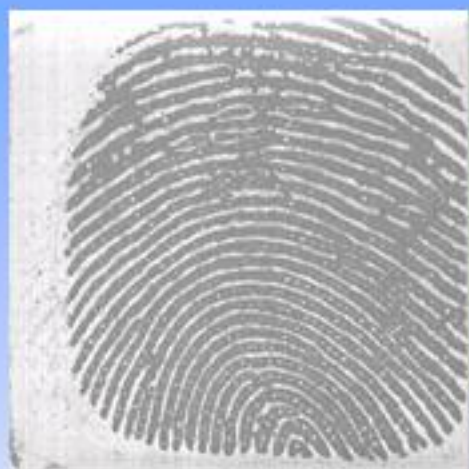
	Average Image Size	Average Minutiae
Input Image	300x300	22
Composite Image	336x332	30

"Good" Examples



"Successful" registration of images

"Poor" Examples



**Unsuccessful registration of
images due to few common
minutiae points**

The Myth of Fingerprints

"They left a mark - on criminology and culture. But what if they're not what they seem?" - *Simon Cole, 2001*

"Only Once during the Existence of Our Solar System Will two Human Beings Be Born with Similar Finger Markings". - *Harper's headline, 1910*

"Two Like Fingerprints Would be Found Only Once Every 10^{48} Years" - *Scientific American, 1911*

Fingerprint identification is based on two premises

- (i) Persistence: fingerprint characteristics are invariant
- (ii) Uniqueness: fingerprint characteristics are unique

The **uniqueness** of fingerprints has been accepted over time because of lack of contradiction and relentless repetition. As a result, fingerprint based identification has been regarded as a perfect system of identification.

Challenge to Fingerprint Individuality

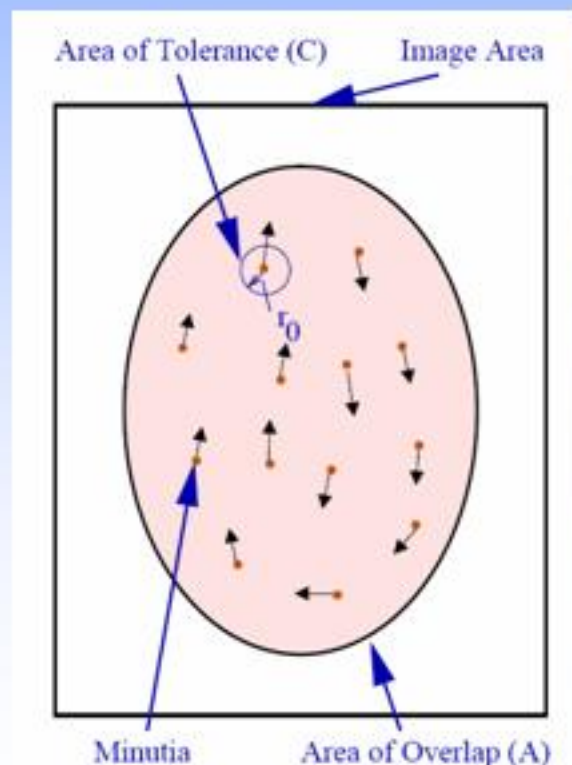
- Factors determining admissibility of expert scientific testimony: (i) Hypothesis testing, (ii) Known or potential error rate, (iii) Peer reviewed and published, (iv) General acceptance (*Daubert vs. Merrell Dow Pharmaceuticals, 1993*)
- Fingerprint identification was challenged under *Daubert*: error rate is not known and the fundamental premise that "Fingerprints are distinctive or unique" has not been put to test (*USA v. Byron Mitchell, 1999*)

Fingerprint Evidence

- On Jan 7, 2002, Louis Pollak, a federal judge in Pennsylvania, decided that fingerprint evidence was unreliable
- Fingerprint examiners, cannot tell the jury point-blank whether prints from defendants and those collected from crime scenes do or do not match
- They could, however, testify how fingerprints were obtained and about similarities or differences between them
- On Mar 13, 2002, Louis Pollak reversed his earlier ruling and ruled that experts could testify that prints lifted from the crime scene came from a particular defendant

Probability of False Correspondence

- Given a fingerprint with n minutiae, what is the probability that it will share q minutiae with another fingerprint containing m minutiae. The corresponding minutiae should "match" in location and orientation.



(a) $M=52$
 $m=n=q=26$
 $P = 2.40 \times 10^{-30}$

(b) $M=52$
 $m=n=26, q=10$
 $P = 5.49 \times 10^{-4}$

$$M = A/C$$

FVC 2004 Results

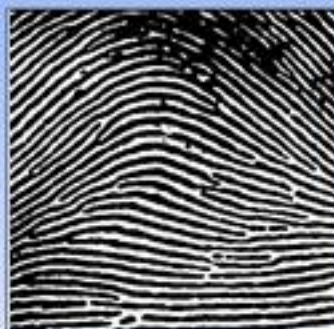
Algorithm	EER(%)	Avg Enroll Time (sec)	Avg Match Time (sec)	Avg Model Size (KB)
Bioscrypt Inc.	2.07	0.08	1.48	24
Sonda Ltd	2.10	2.07	2.07	1.3
Chinese Academy of Sciences	2.30	0.35	0.67	16.4
Gevarius	2.45	0.69	0.71	2.0
Jan Lunter	2.90	1.01	1.19	3.1

- **Database:**

- DB1: optical sensor "V300" by CrossMatch
- DB2: optical sensor "U.are.U 4000" by Digital Persona
- DB3: thermal sweeping sensor "FingerChip FCD4B14CB" by Atmel
- DB4: synthetic fingerprints

Fingerprint Classification

- Classify fingerprints for **binning/indexing**
- Goal: 99% classification accuracy with 20% reject rate
- Even experts cannot always do correct classification



Arch (A)



Tented Arch (T)



Right Loop (R)



Left Loop (L)



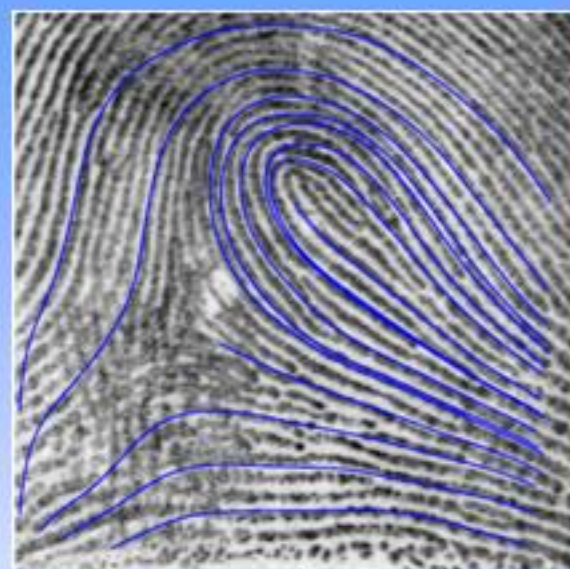
Whorl (W)



Double Loop (W)

- Natural frequencies of W, L, R and A (A + T) are 27.9%, 33.8%, 31.7% and 6.6%

Classification Using Orientation Field Flow Curves



Input Fingerprint

Estimate
Orientation Field

Generate OFFCs

A, L, R, or W

Classify
fingerprint

Isometric maps
and features

Orientation Field Flow Curves

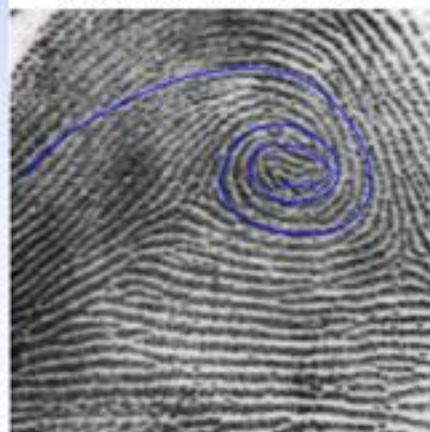
- Study the topology of the curves formed by ridges
- OFFC is a curve inside a fingerprint image whose tangent direction is parallel to the direction of the orientation field
- Starting points of OFFCs are chosen along the vertical and horizontal lines passing through the midsection of the image



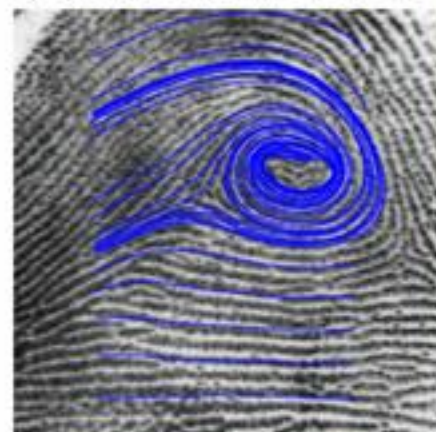
(a) Input image



(b) orientation field

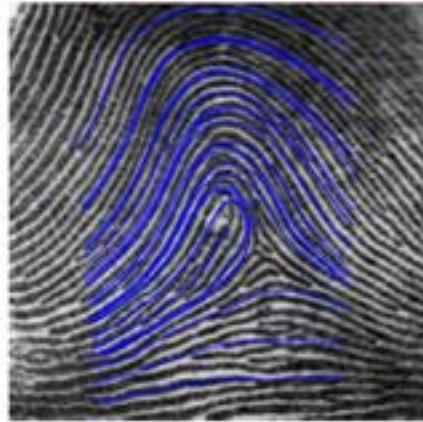


(c) one OFFC

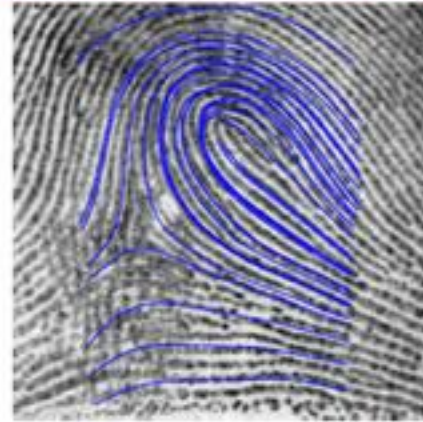


(d) some OFFCs

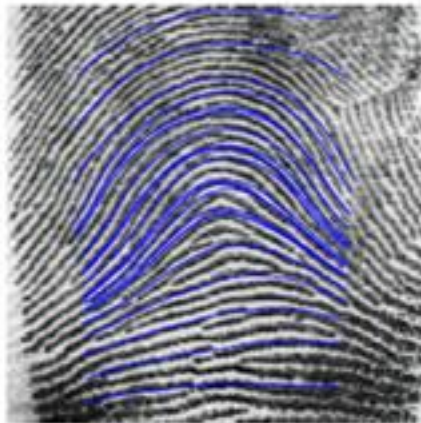
Orientation Field Flow Curves



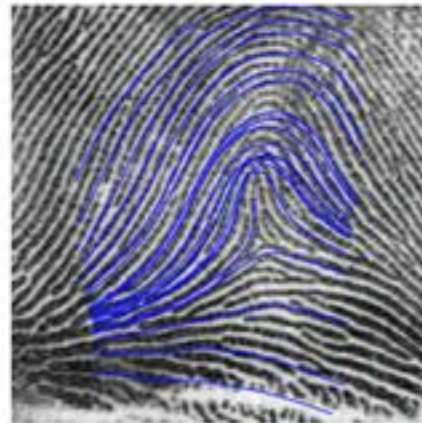
(a) left-loop



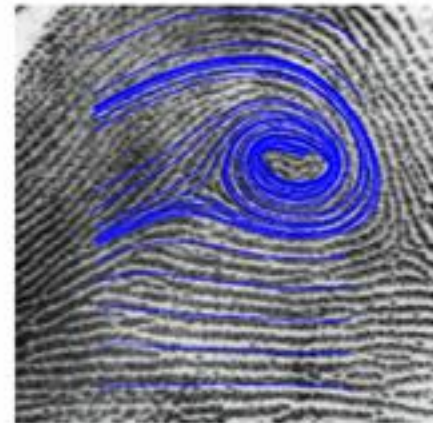
(b) right-loop



(c) plain arch



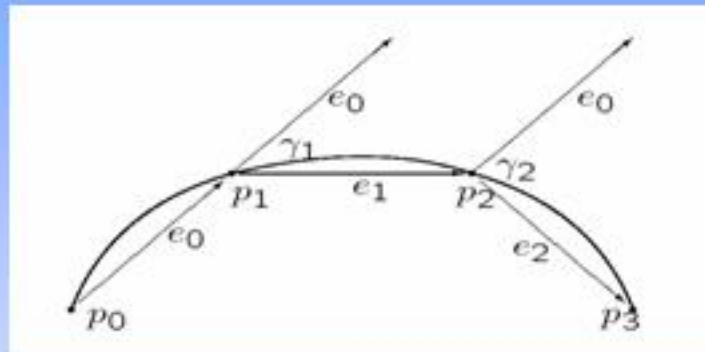
(d) tented arch



(e) whorl

Isometric Maps

- Geometric characteristics of OFFCs are captured by the changes occurring in the tangent space as we traverse along OFFC

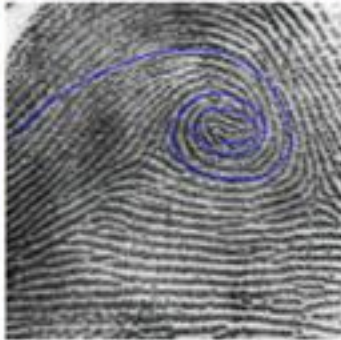


- Let $p_j = (x_j; y_j)$, $j = 0, 1, 2, \dots, N$ be equidistant points (at a distance δ) on the OFFC
- Approximate the tangent vector at p_i by the chord vector:

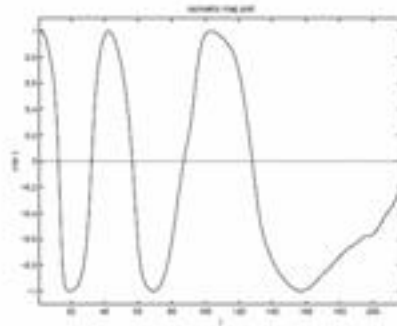
$$V_{p_j} \equiv \frac{1}{\delta}(x_{j+1} - x_j, y_{j+1} - y_j)^T$$

The unit vector is $e_j = V_{p_j} / ||V_{p_j}||$. Obtain the isometric maps in terms of rotation angles γ_j with $\cos \gamma_j = e_0 \bullet e_j$, where \bullet is the Euclidean inner product on \mathbb{R}^2

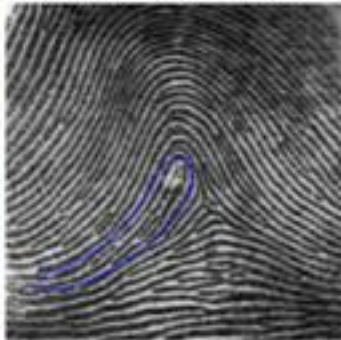
Isometric Maps



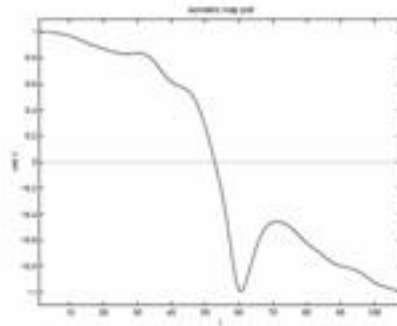
(a) curve type: whorl



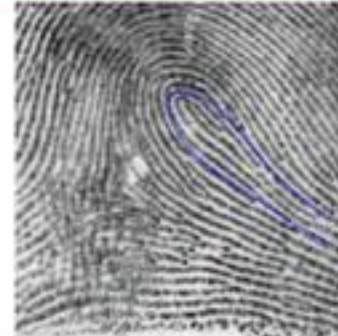
(b) isometric map



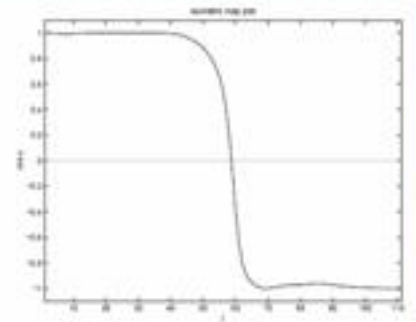
(c) curve type: left-loop



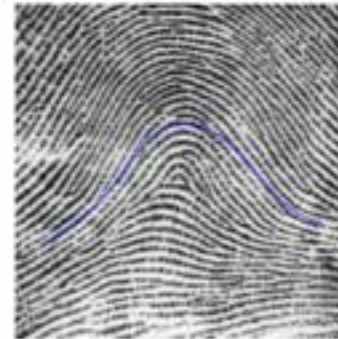
(d) isometric map



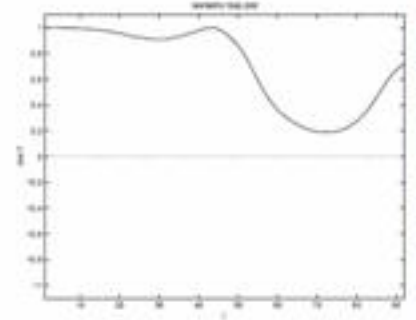
(a) curve type: right-loop



(b) isometric map



(c) curve type: arch



(b) isometric map

Classification Results

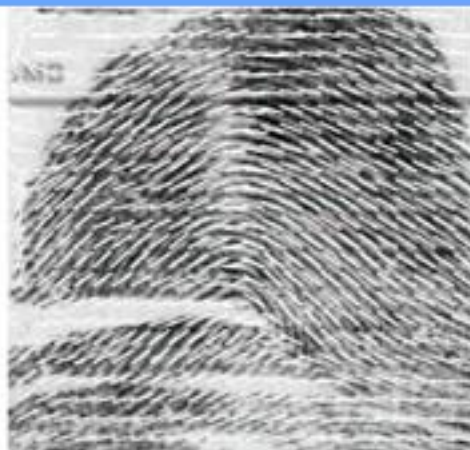
- No. of sign-change points, values of the local max/min between sign-change points are potential features
- NIST 4 database containing 2,000 fingerprint image pairs
- 800 fingerprints from each of the 5 classes: W, L, R, A and T
- Classification accuracy into 4 classes: 94.4%.

True/Assigned	A	L	R	W	Accuracy (%)
A	797	2	1	0	99.62
T	781	19	0	0	97.62
L	63	730	1	6	91.25
R	75	4	720	1	90.00
W	12	23	18	747	93.34

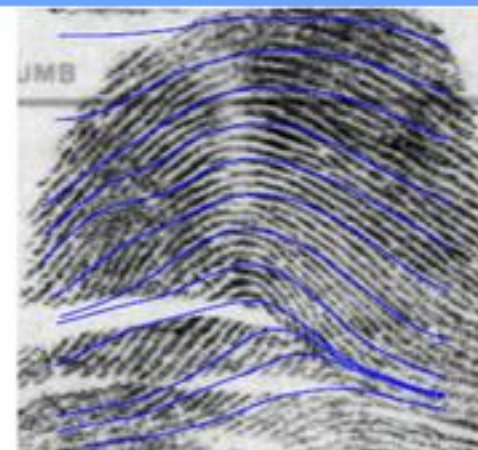
Classification Errors



(a) Input image



(b) Orientation field



(c) OFFCs

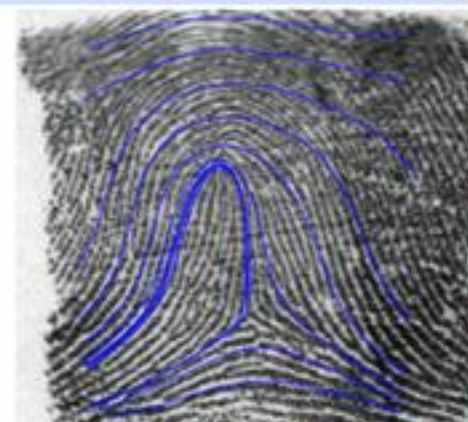
Oversmoothing of orientation field: True class: L; Assigned class: A



(a) Input image



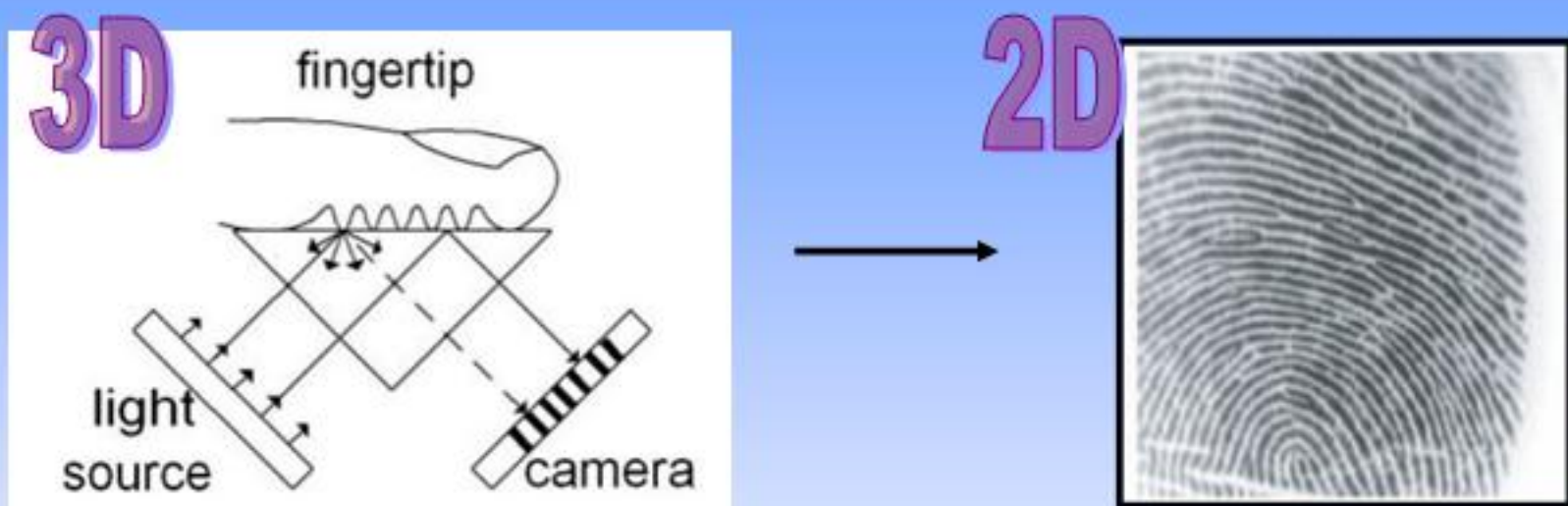
(b) Orientation field



(c) OFFCs

Detection of spurious loops: True class: A; Assigned class: L

Fingerprint Deformation

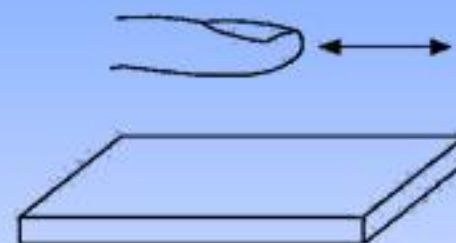
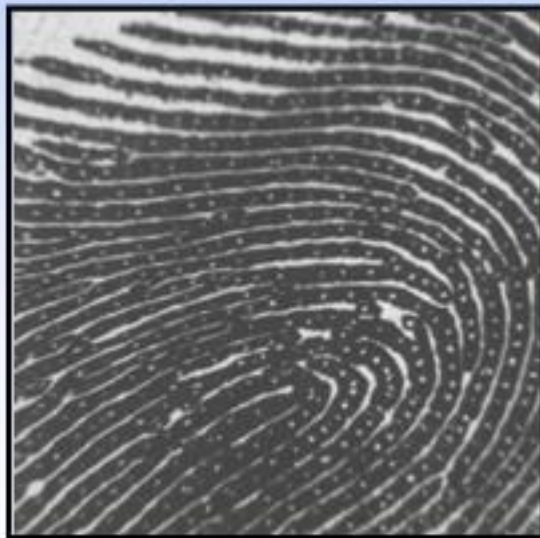
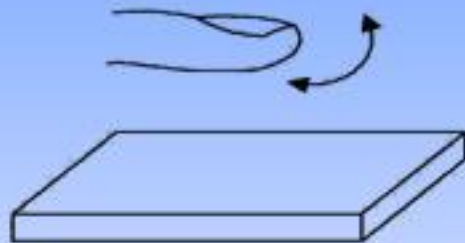


Causes:

- ◆ Elasticity of skin
- ◆ Amount of pressure applied by the subject
- ◆ Movement of fingertips during capturing

On-line Deformation Demo

- Non-linear Rotation
- Non-linear lateral movement



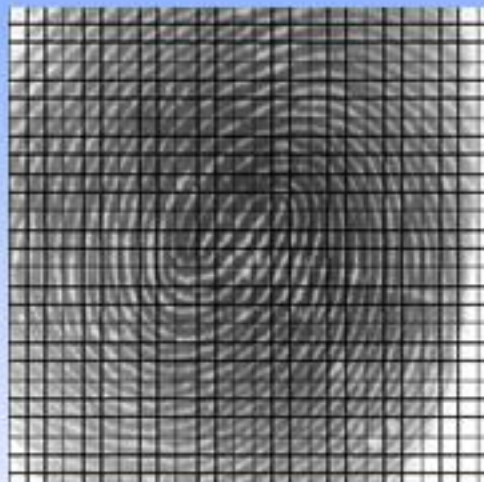
<http://www.cim.mcgill.ca/~vleves/homepage/>

Non-linear deformation

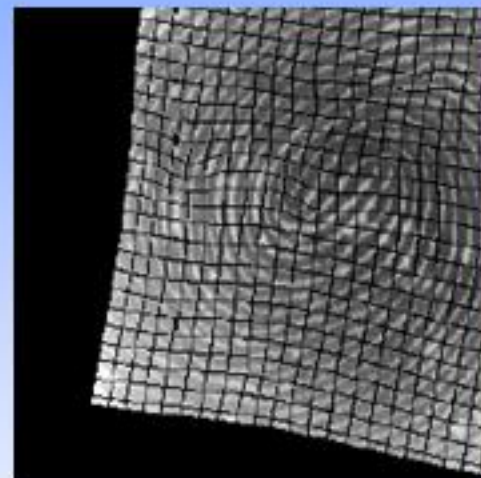
- In order to align (register) two impressions of a finger, the non-linear deformations in the ridge structure have to be considered



(a) Template image



(b) Query image



(c) Aligning query with template

Average Deformation Model

- Given several impressions of a finger, we develop a finger-specific “average” deformation model
- The average deformation model allows us to pre-distort the template minutiae points before matching them with the query minutiae points
- The deformation model is developed using Thin Plate Splines (TPS)
- Minutiae points and ridge curves are used to establish correspondences between pairs of impressions

Average deformation

- 16 impressions pertaining to a single finger



Baseline impression

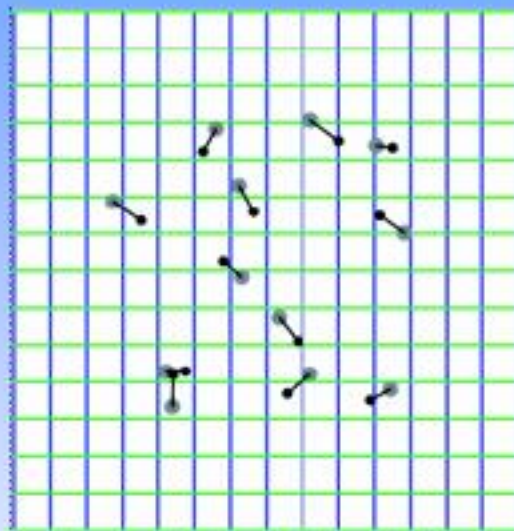


Target impressions

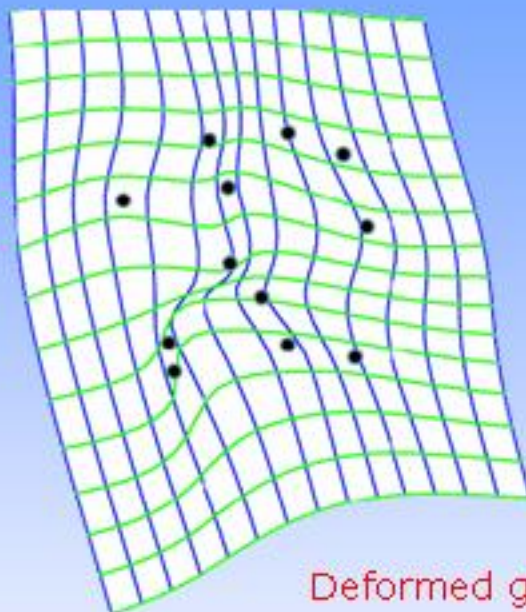
- We compute the “average” deformation that relates the baseline impression with the target impressions

Thin Plate Splines

(Rohr et al. 2001)



Control point pairs



Deformed grid

Given 12 control points:

- TPS is first applied to x-axis and y-axis separately to interpolate the displacement surface given the displacements of control points. Obtain the deformation parameters
- The two interpolated surfaces are then combined to provide displacements for all the points on the grid

The TPS model

- Consider a pair of point patterns $U=\{u_1, u_2, \dots, u_n\}$ and $V=\{v_1, v_2, \dots, v_n\}$, where (u_k, v_k) is the k^{th} corresponding pair; goal is to learn the transformation F , s.t. $F(u_k) = v_k$, for $k=1, 2, \dots, n$
- The Thin Plate Spline (TPS) model is given by,

$$F(u) = c + Au + W^T s(u),$$

where

c is a 2x1 translation vector,

A is a 2x2 affine matrix, and

W^T is a $n \times 2$ weighting matrix;

$$s(u) = (\sigma(u-u_1), \sigma(u-u_2), \dots, \sigma(u-u_n))^T$$

$$\sigma(u) = \begin{cases} ||u||^2 \log(||u||), & ||u|| > 0 \\ 0, & ||u|| = 0 \end{cases}$$

Estimating parameters of TPS

- We solve the following equation:

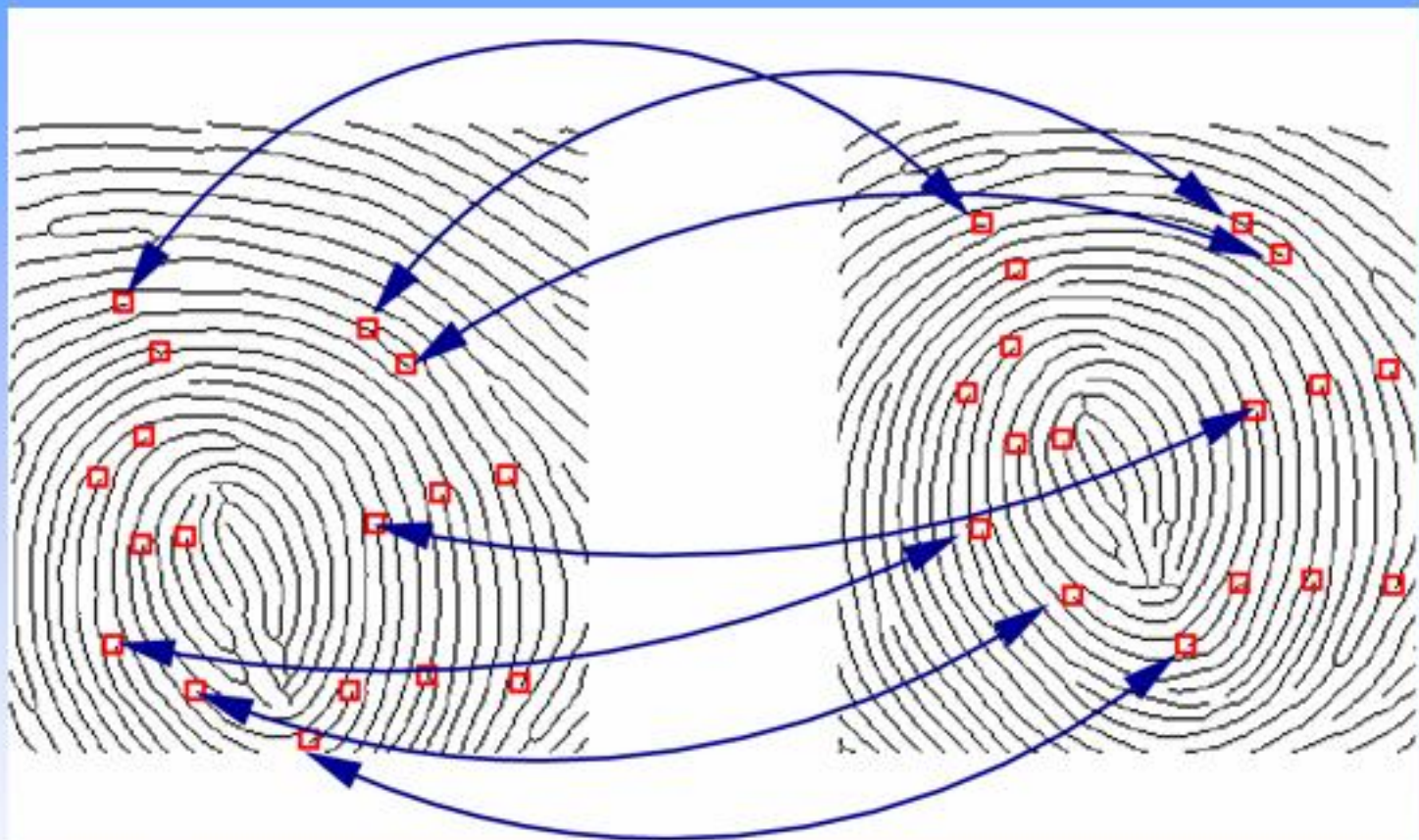
$$\begin{bmatrix} H_{n \times n} & \mathbf{1}_n & U \\ \mathbf{1}_n^T & 0 & 0 \\ U^T & 0 & 0 \end{bmatrix} \begin{bmatrix} W_{n \times 2} \\ c_{2 \times 1}^T \\ A_{2 \times 2}^T \end{bmatrix} = \begin{bmatrix} V \\ 0 \\ 0 \end{bmatrix}, H_{i,j} = \sigma(u_i - u_j)$$

- The constraints are:

$$\mathbf{1}_n^T W = 0$$

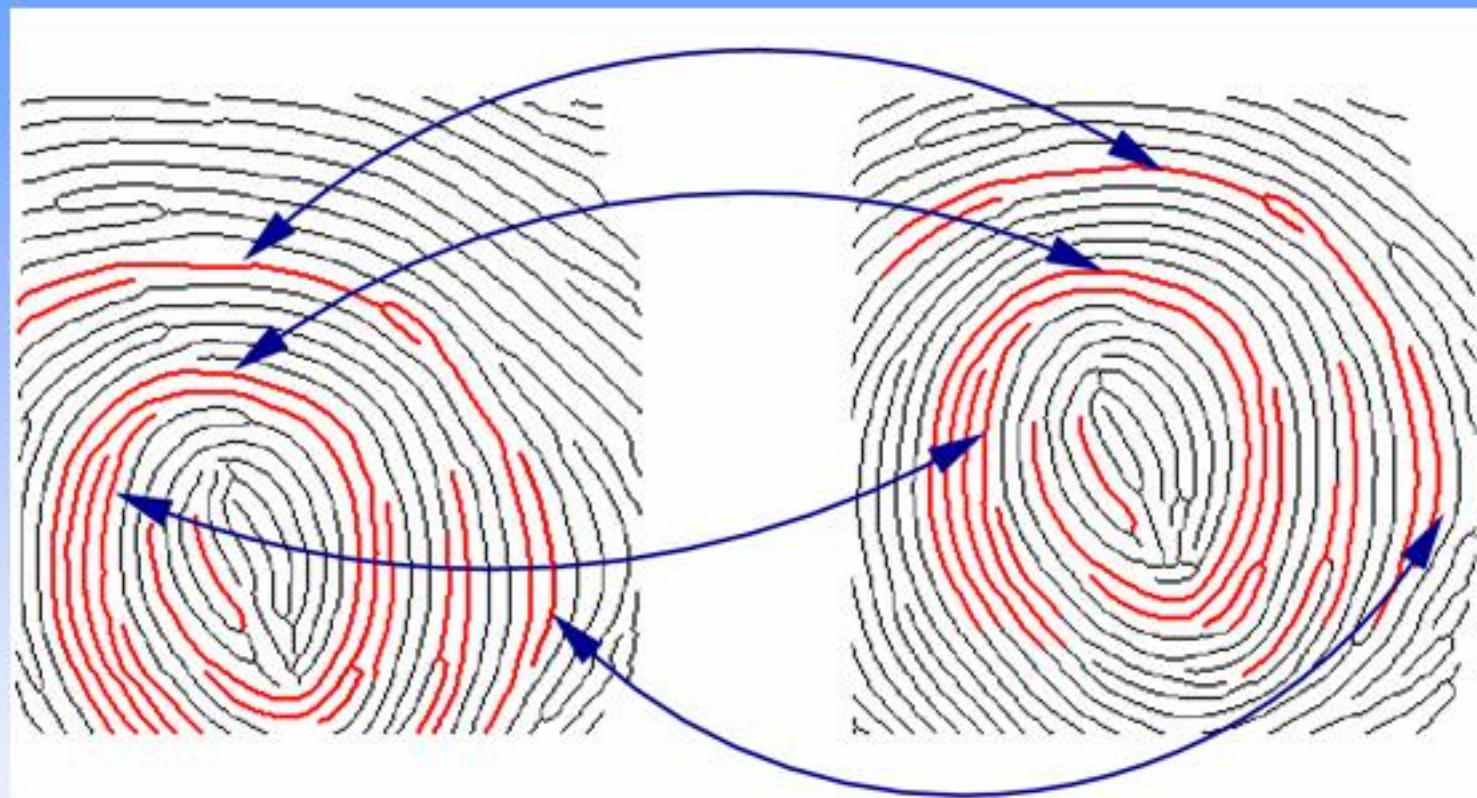
$$U_n^T W = 0$$

Minutiae correspondences



- The TPS model requires point correspondences between image pairs
- We use an elastic string matching technique to obtain minutiae point correspondences

Ridge curve correspondences



- Ridge curve correspondences are next determined by tracing the ridges in the vicinity of corresponding minutiae points
- These ridge curves are then sampled at regular intervals to obtain point correspondences

Alignment using TPS



(a) Alignment using TPS when minutiae correspondences are used



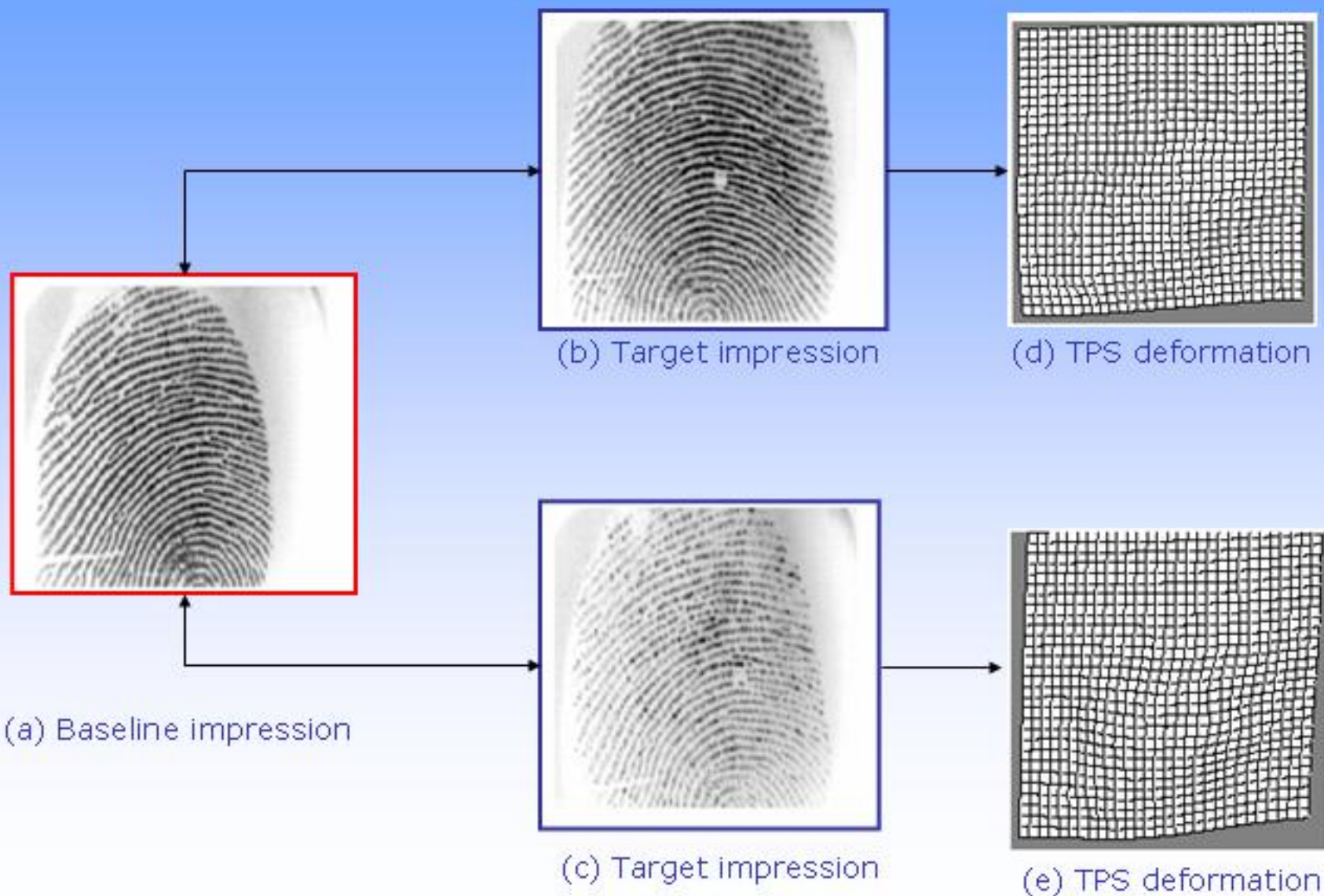
(b) Alignment using TPS when ridge curve correspondences are used

The average deformation model

- Suppose we have L impressions of a finger: T_1, T_2, \dots, T_L .
- An impression, T_i , can be paired with each of the remaining $(L-1)$ impressions
- For each pairing $\{T_i, T_j\}, j \neq i$, a TPS model, F_{ij} , is computed using sampled ridge curve correspondences
- The average deformation of each pixel u in T_i can then be computed as:

$$\bar{F}_i(u) = \frac{1}{L-1} \sum_{j \neq i} F_{ij}(u).$$

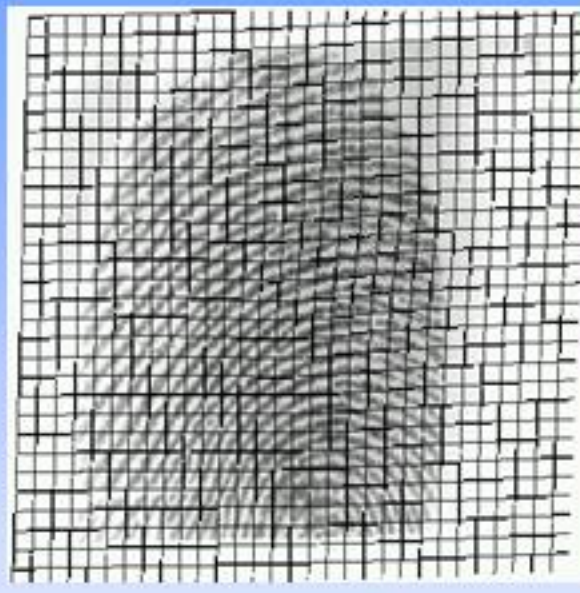
Non-linear deformation



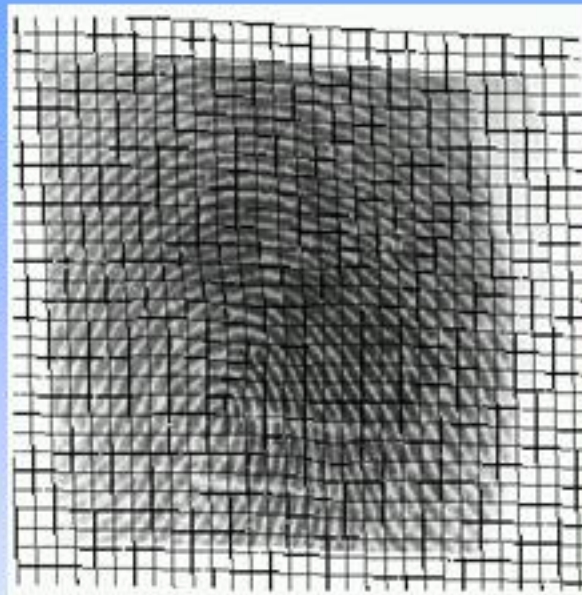
Average deformation model



Finger 1



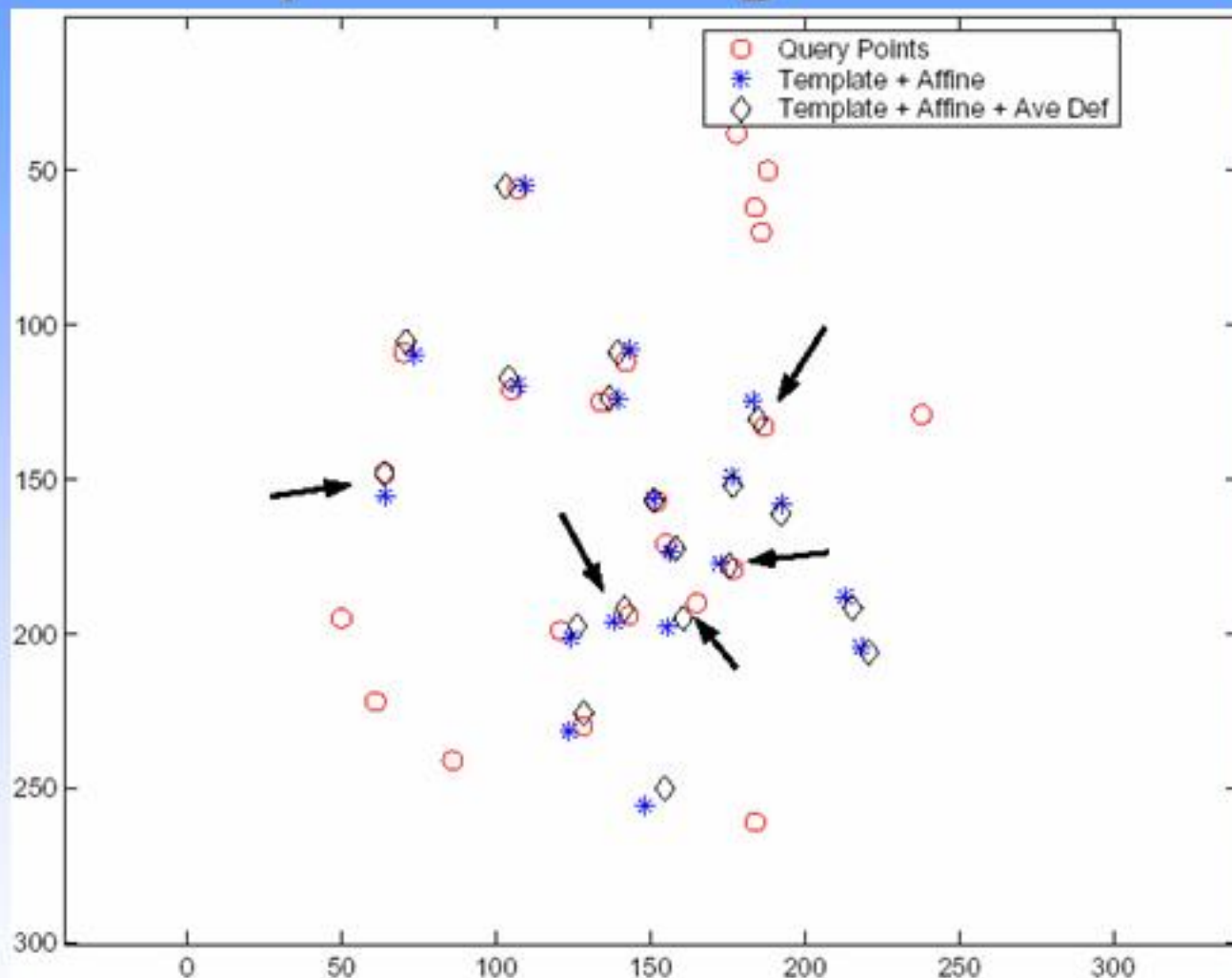
Finger 2



Finger 3

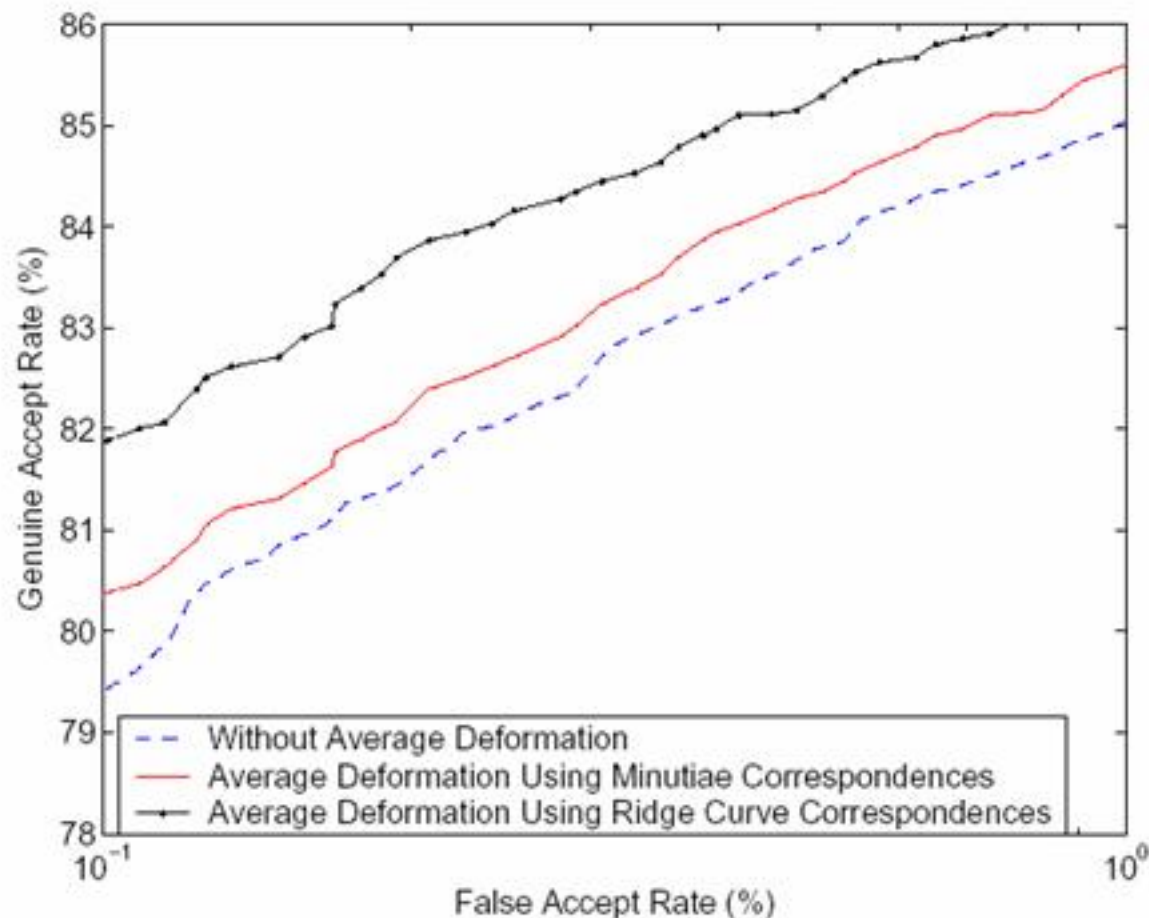
- The average deformation model of three different baseline impressions is shown; each baseline impression was compared against 15 other impressions of the same finger in order to compute the model

Improved alignment



- The average deformable model results in an improved alignment between query and template minutiae points

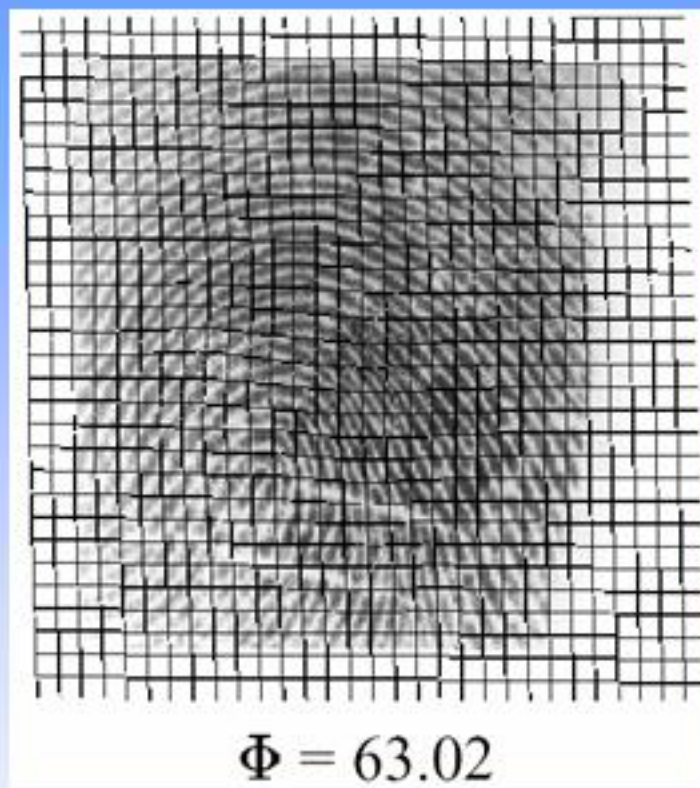
Matching performance



- Data of 50 fingers acquired using Identix sensor
- 32 impressions per finger
- 16 impressions used for computing the average deformation of a finger
- 16 impressions used in testing

- Using distorted minutiae templates results in better alignment

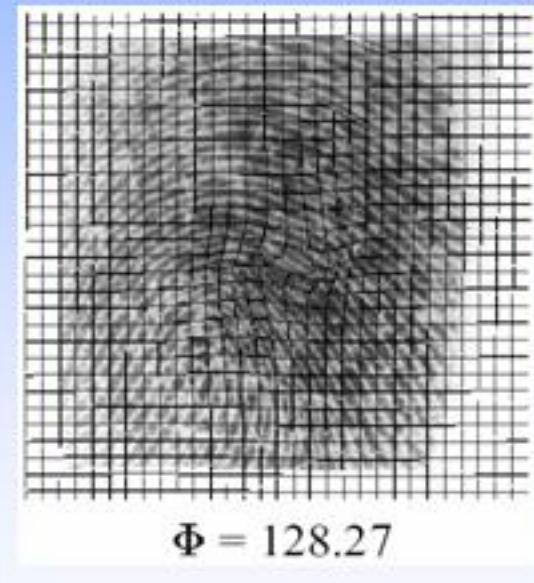
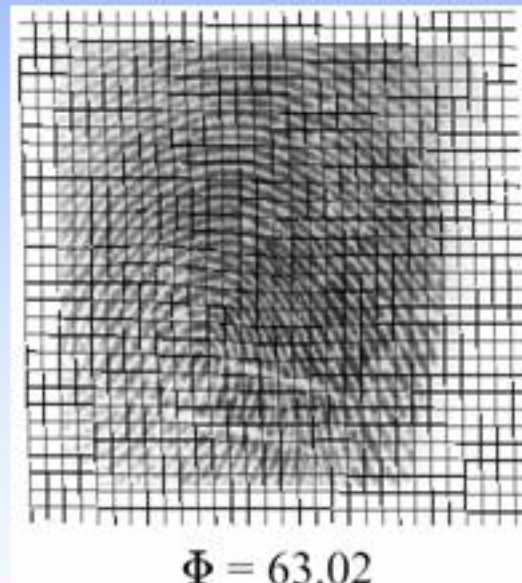
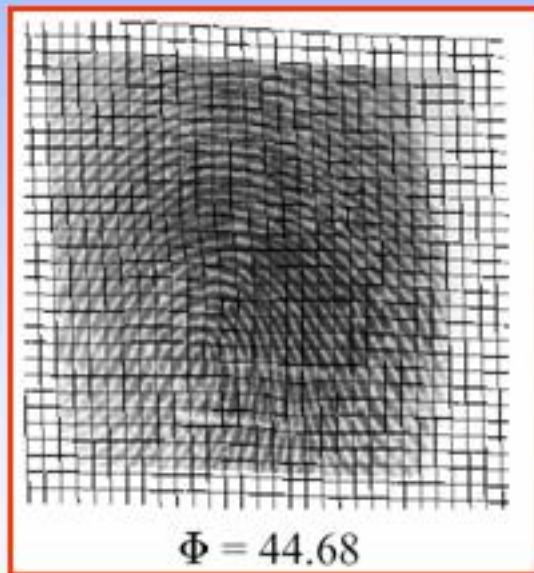
Index of deformation (Φ)



- The index of deformation represents the variability associated with the estimated deformation around the average
- The index of deformation (Φ) is the sum of the trace of the covariance matrix of deformation over all the pixels

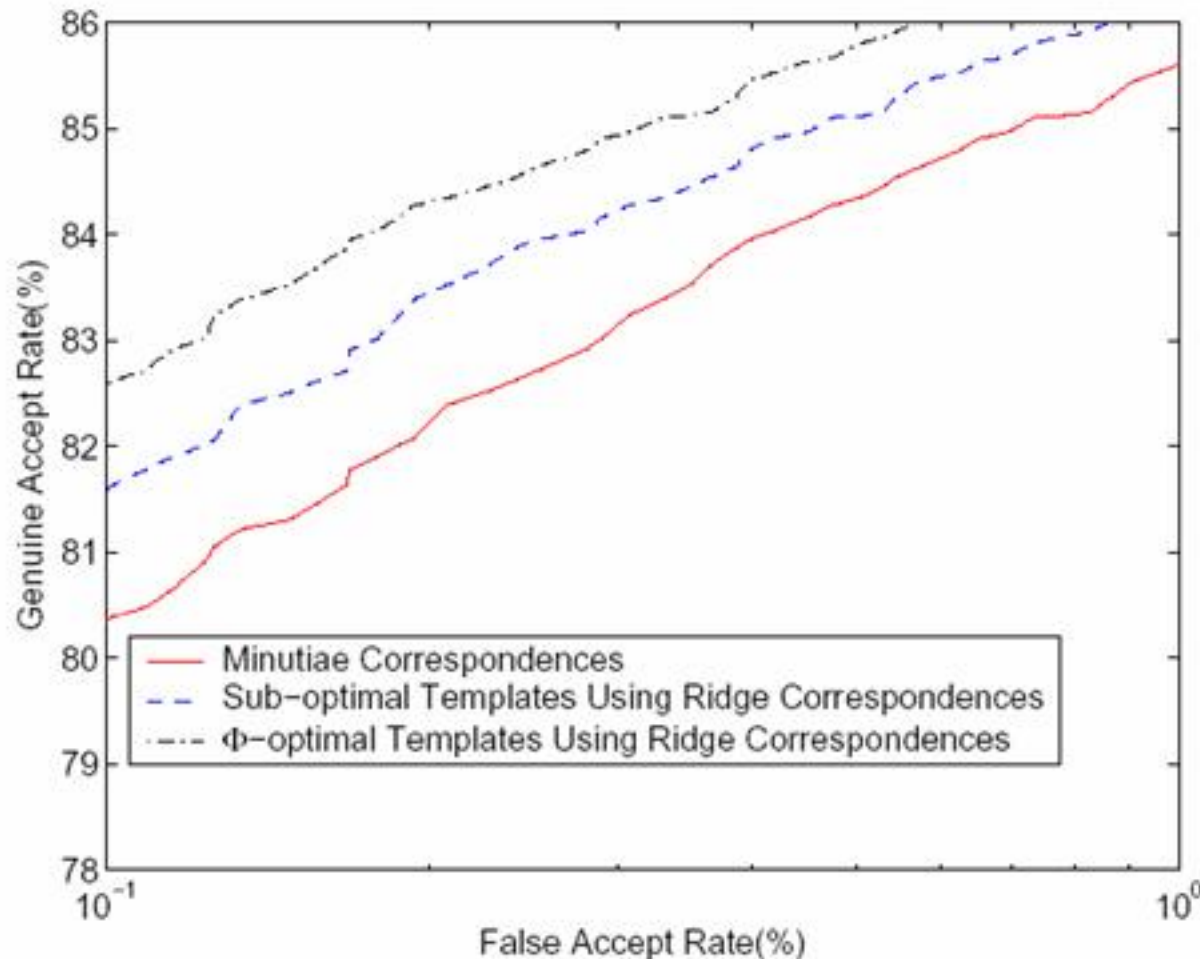
Template selection

- Given L enrollment images of a finger, select a template such that its index of deformation, Φ , w.r.t. other images is the smallest. Store the average deformable model of this template



Selected template

Performance using Φ -optimal templates

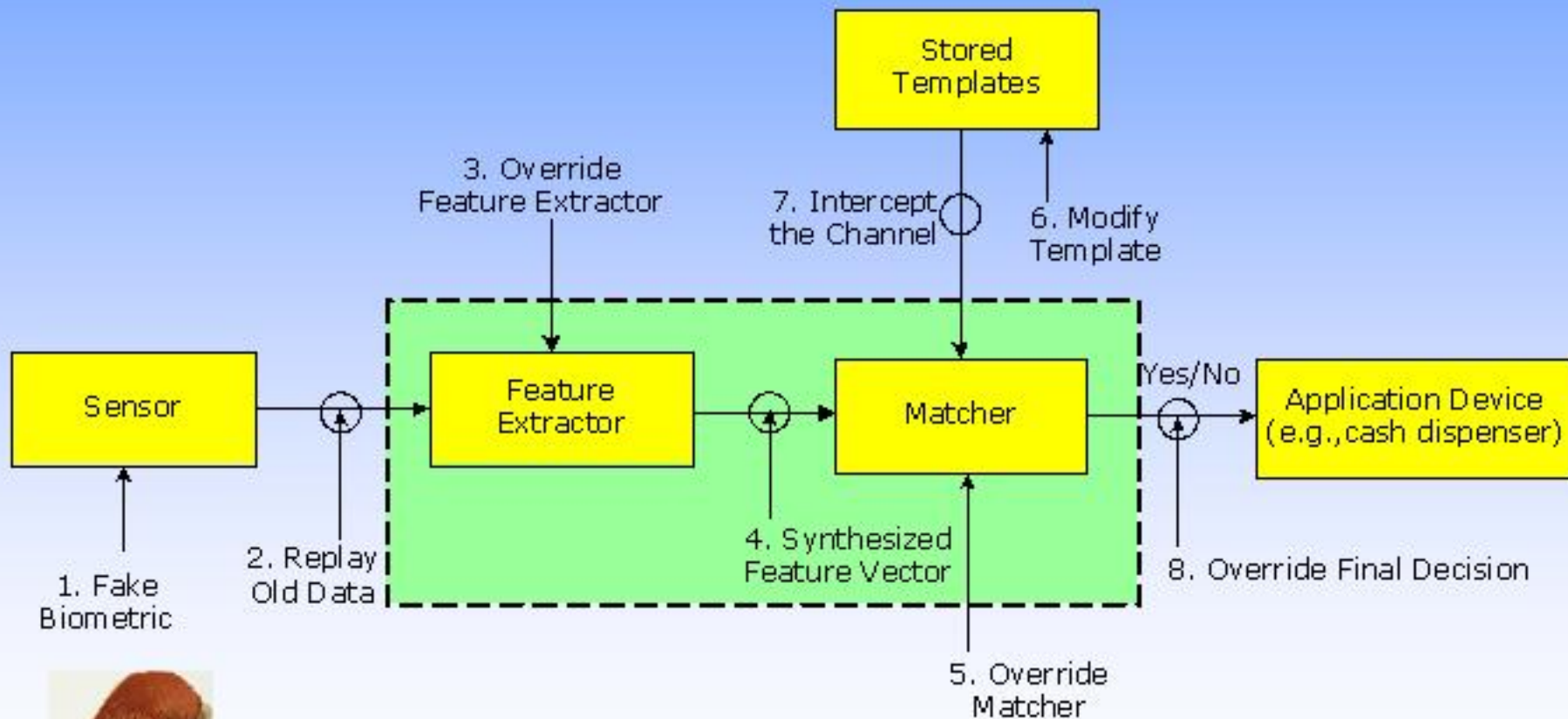


- Data of 50 fingers acquired using Identix sensor
- 32 impressions per finger
- 16 impressions used for computing the average deformation of a finger
- 16 impressions used in testing

- Using the Φ -optimal templates results in better performance

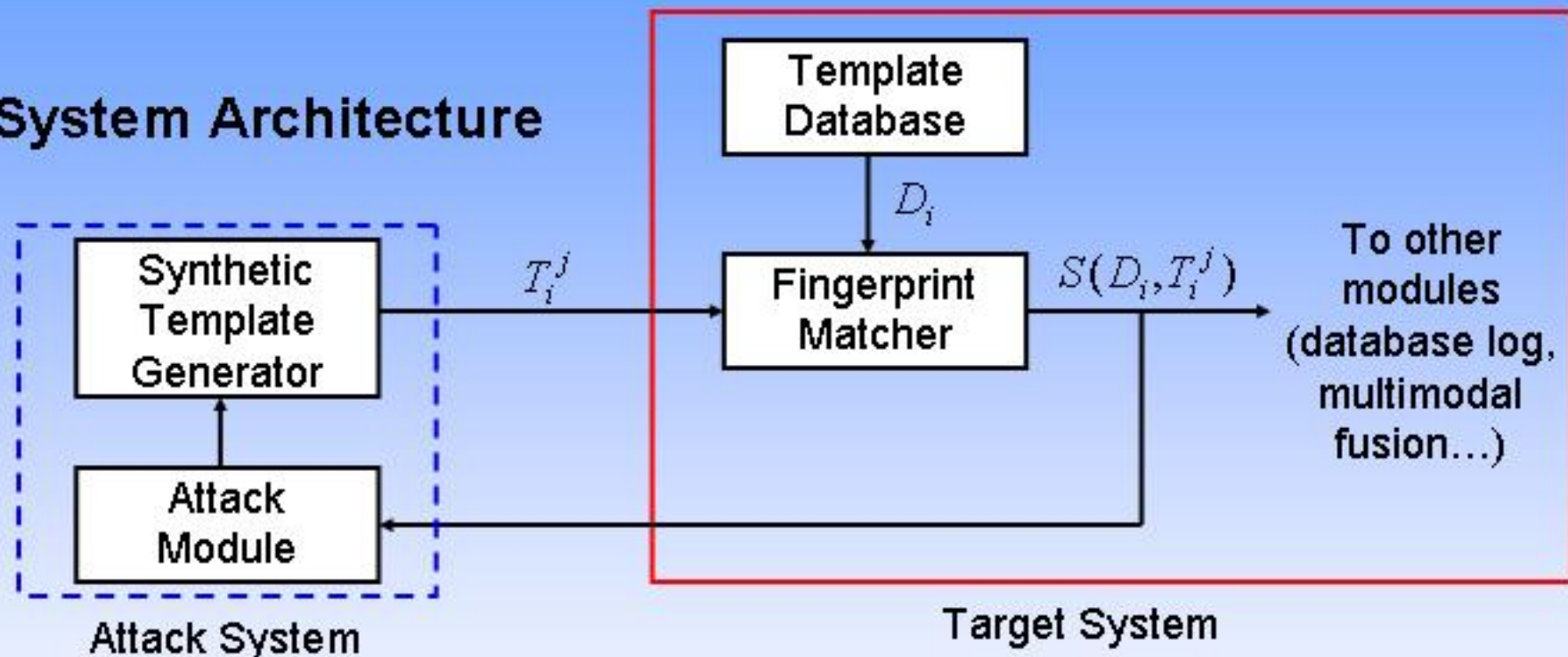
Data Security

Attacks on Biometric Systems



Hill Climbing Attack

System Architecture



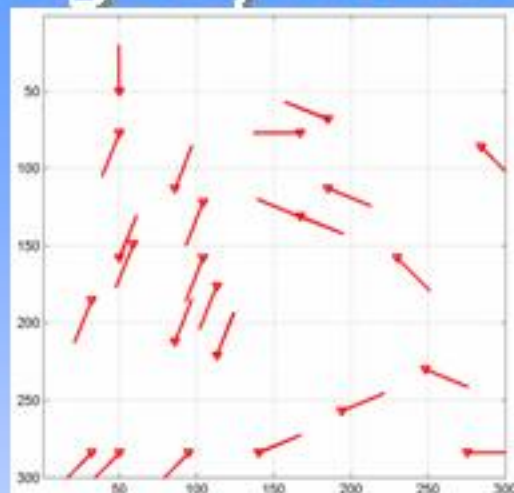
D_i : Database template corresponding to user i

T_i^j : j^{th} synthetic template generated for user i

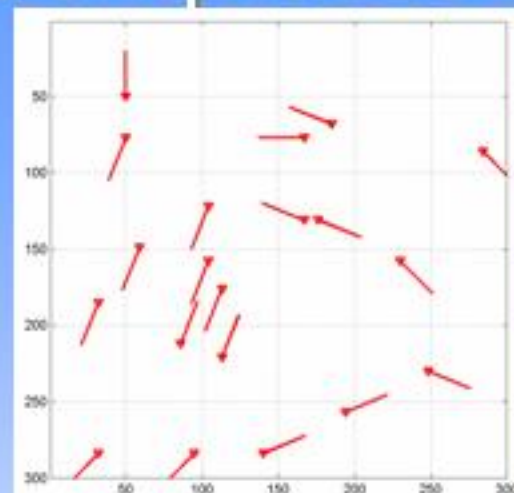
Generating Synthetic Templates



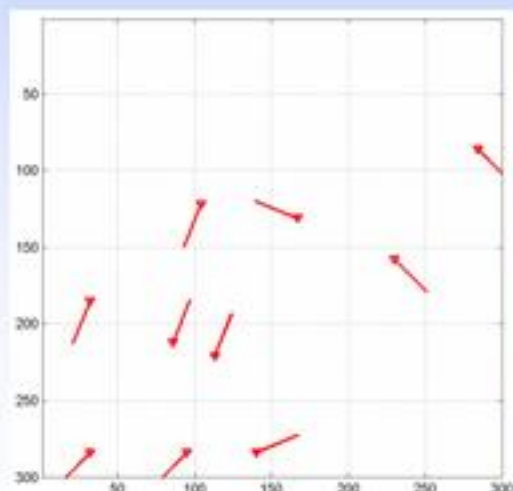
Original image with
minutiae



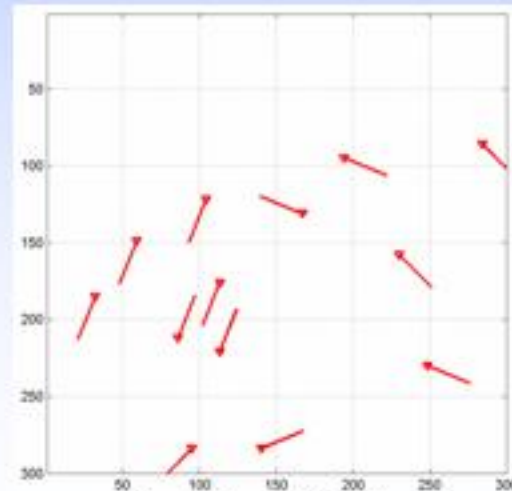
Best initial guess
(score: 5.6)



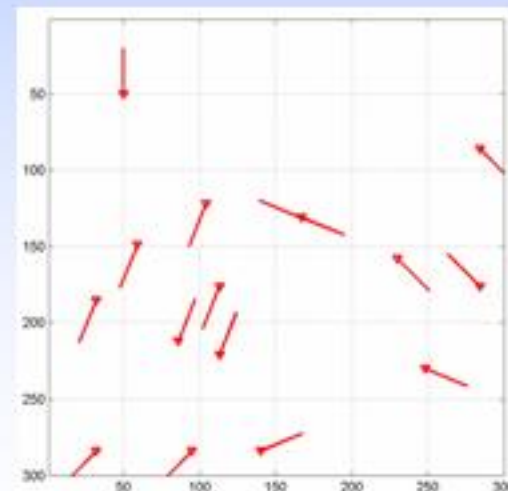
Iteration 125
(score: 7)



Iteration 192
(score: 13.3)

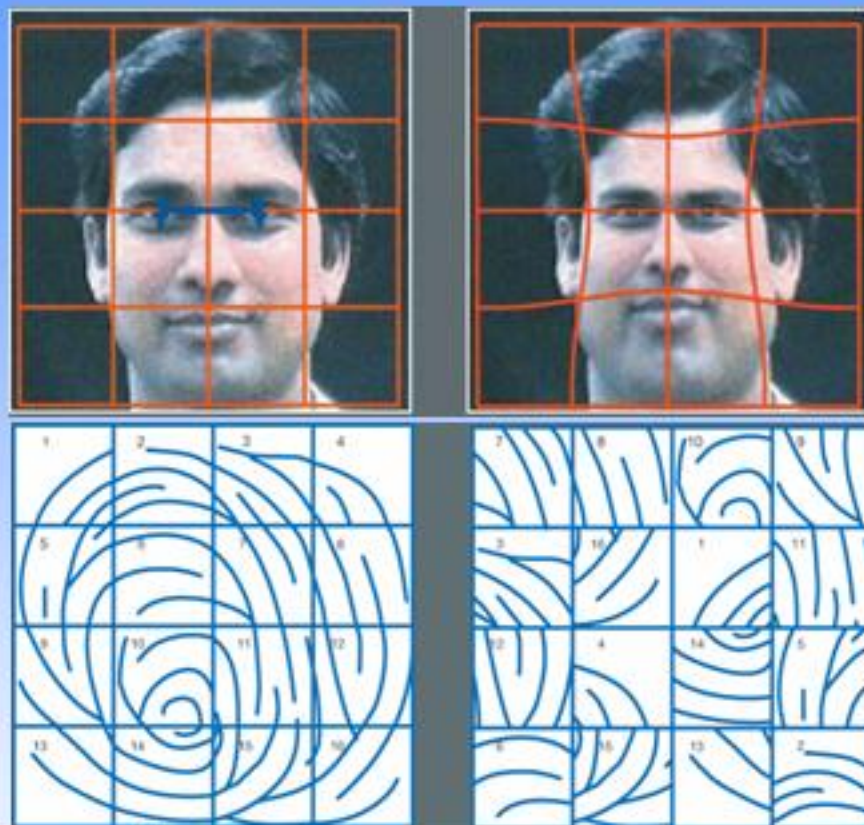


Iteration 175
(score: 10.5)



Iteration 150
(score: 8.6)

Template Protection



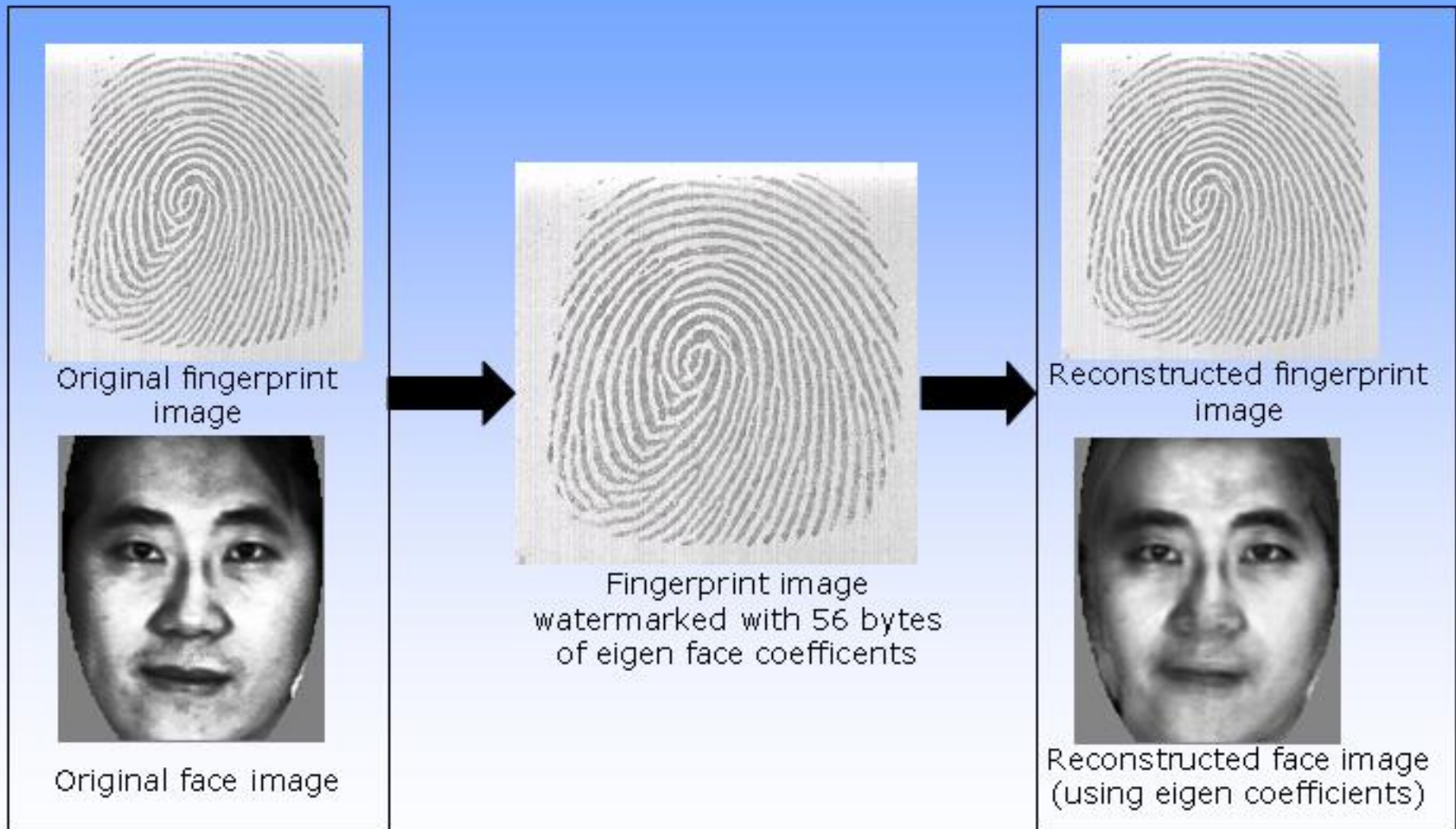
© Ratha, Connell, Bolle (IBM)

- Encrypting or watermarking templates in the database
- Storing only a transformed version of a user's template to protect the original template

Jain, Uludag, Hsu, "Hiding a Face in a Fingerprint Image", *Proc. of ICPR*, Aug., 2002

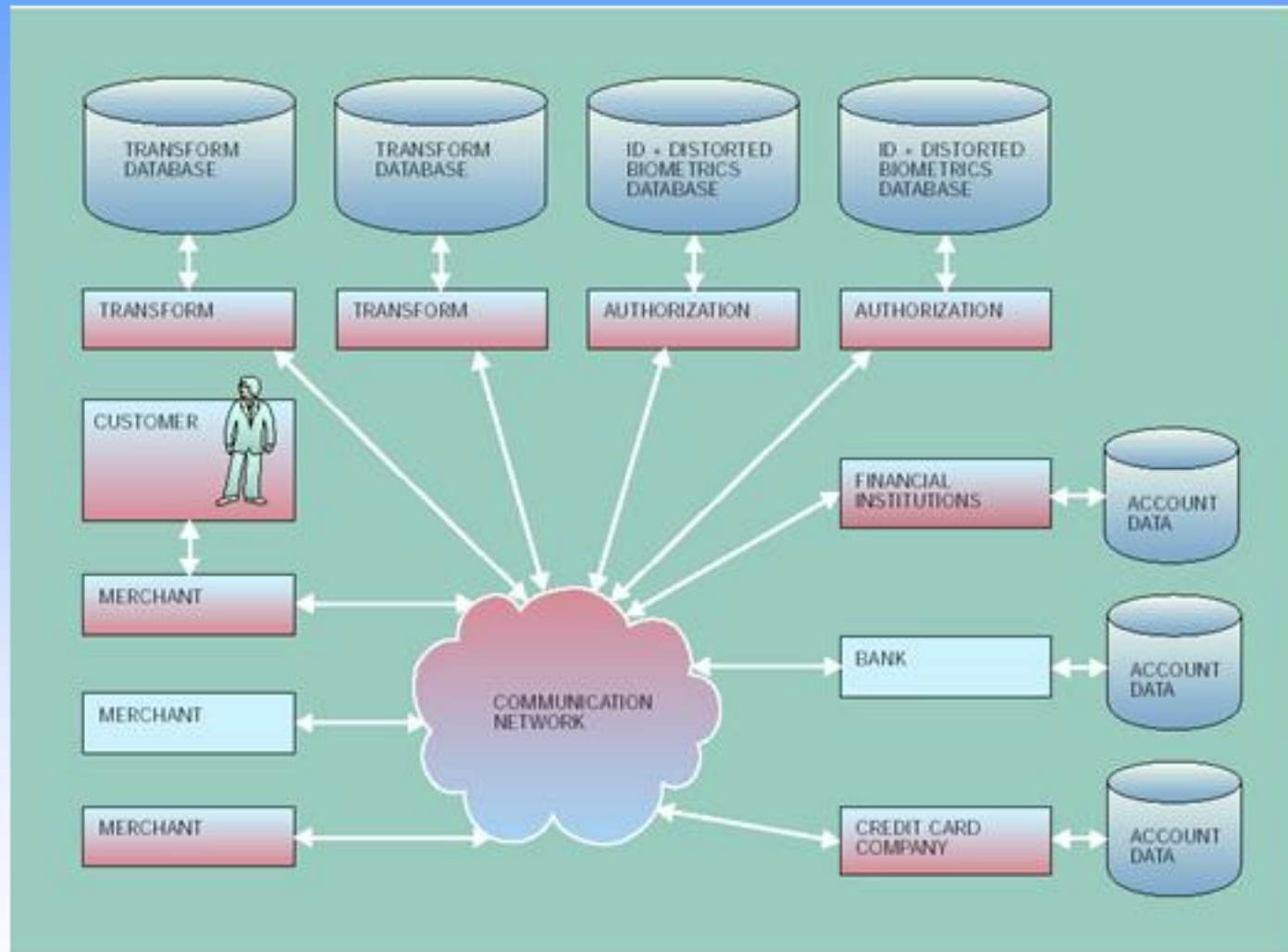
Ratha, Connell, Bolle, "Enhancing security and privacy in biometrics-based authentication systems", *IBM Systems Journal*, vol. 40, no. 3, 2001, pp. 614-634.

Watermarking Fingerprints



Jain, Uludag, "Hiding Biometric Data", IEEE Trans on PAMI, Nov 2003

Cancelable Biometrics



© Ratha, Connell, Bolle (IBM)

Taken from Ratha, Connell, Bolle, "Enhancing security and privacy in biometrics-based authentication systems", IBM Systems Journal, vol. 40, no. 3, 2001, pp. 614-634.

Liveness Detection

- Fingerprint: temperature sensing; detection of pulsation on fingertip; pulse oximetry; electrical conductivity of skin
- Voice: matching the lip movement (video) to the audio; repeating randomly generated sequence of digits and phrases
- Face: Expression change; pose change
- Iris: Blinking eyes; saccadic movements
- Multimodal biometrics makes it difficult for an intruder to spoof multiple traits simultaneously

Summary and Future Directions

Summary

- Reliable and automatic user authentication is becoming a necessity; emerging applications include homeland security, e-banking, Internet shopping, instant credit approval, ATM cash withdrawal, e-cash and computer data security
- Biometric-based identification has come a long way since fingerprints were introduced more than 100 years back
- The present need is for automated systems that can operate in a remote environment in an unattended scenario
- There is a popular misconception that fingerprint identification is a fully solved problem

Summary

- Fingerprint **matching** can be accomplished in several different ways: minutiae-based, texture-based, correlation-based, hybrid
- Fingerprint **classification and indexing** schemes are necessary to reduce the number of matching operations in an identification scenario
- Need more tests like FVC 2004 and FVPTE to compare and evaluate systems
- Develop systems capable of handling spoof attacks in unsupervised applications
- Need to ensure that the user's privacy and biometric information is secured (encryption, digital watermarking, cancelable biometric)

Future Directions

- Representation:
 - How can the fingerprint of a person be effectively modeled using the limited number of samples obtained during enrolment?
- Scaling:
 - Can one reliably predict the performance (accuracy, speed, vulnerability) of a large-scale biometric system that has several million identities enrolled in it?
- Security:
 - How does one ensure security of the templates stored in a database?
- Privacy:
 - Will fingerprint databases be cross-linked? Will minutiae template data be used to reconstruct fingerprints?

Research Directions

- Fingerprint indexing: novel schemes
- Fingerprint deformation: estimation and removal
- Fingerprint quality: incorporate quality during matching
- Multibiometrics: fingerprint in conjunction with other traits
- Fingerprint template protection schemes
- Fingerprint cryptosystems