FINGERPRINT IDENTIFICATION

Fingerprints have been used for identification of people for a long time. Every individual has unique fingerprints, and they do not change throughout one's lifetime. Hence, fingerprints constitute the fundamental "signature" of a person. Therefore, they are used for positive identification by legal and investigative agencies worldwide. Identification of fingerprints (FP) is carried out by specially trained (human) experts. There is an increasing demand for faster fingerprint identification in many applications, for personal identification in courts of law, to resolve disputed documents, for the issue of passports, for criminal background checks, for access control and security systems, and for corpse identification. Because fingerprints are so commonly used to identify people, the word "fingerprint" has become synonymous as a signature of anything, not just for people alone.

Figure 1 is a picture of a fingerprint impression. The dark lines in the picture are called ridges or ridgelines. The intervening white lines are called valleys. The center of the pattern formed by the ridgeline flow is called a core. The region where the ridgelines flow in three directions is known as a delta. All fingerprints do not necessarily have a core and/or a delta. It depends on the type of fingerprint pattern.

FINGERPRINT PATTERNS

Based on the nature of the flow of ridgelines, and the presence of core points and delta points, fingerprint patterns are classified into a number of pattern classes. There are about eight classes; whorl, twin loop, left loop, right loop, plain arch, tented arch, and composite or accidental. Pictures of all of these patterns are shown in Fig. 2. The distribution and occurrence of these patterns vary widely. According to one estimate an approximate percentage distribution of these patterns is as follows: whorls 35%, left loops 25%, right loops 25%, arches (both plain arch and tented arch) 5%, twin loops 5%, and composites 5%. These classes can be grouped as follows:

- Arch patterns
  - Plain arch
  - Tented arch
- Loop patterns
  - Left loop
  - Right loop
- Whorl patterns
- Twin-loop pattern
- Accidental pattern

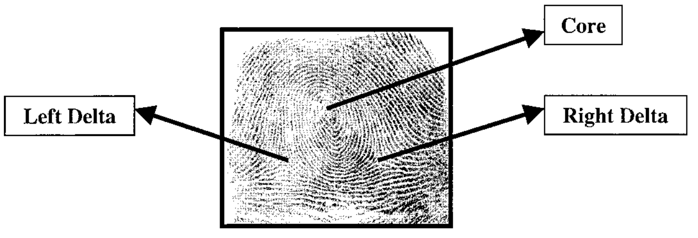


Figure 1. A picture of a fingerprint impression showing the core point and right and left delta points.

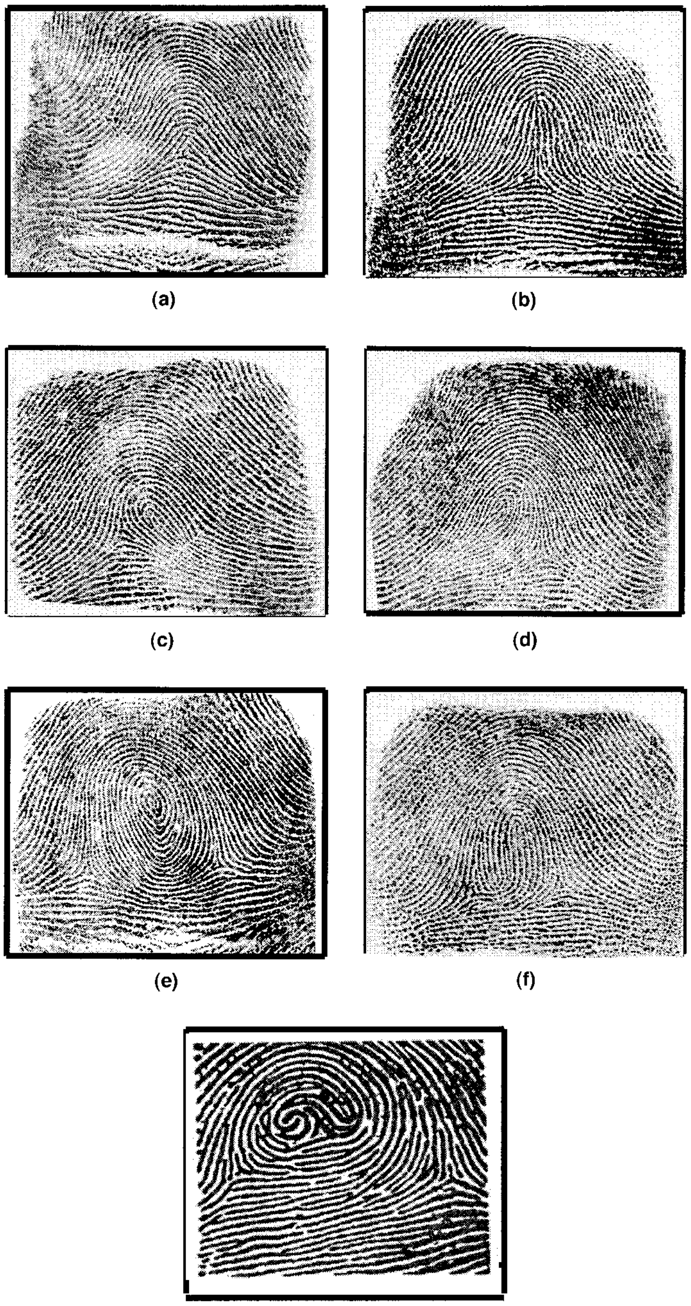


Figure 2. Pictures showing different fingerprint patterns: (a) plain arch; (b) tented arch; (c) left loop; (d) right loop; (e) whorl; (f) twin loop; and (g) accidental pattern.

Arch patterns have no core or delta points. Loop patterns each have a delta and a core point. In the left loop, the delta is on the left side of the core point, and in the right loop the delta is on the right side of the core point. A whole pattern has a core point and two delta points, one each on the left and right sides of the core point. A twin loop has two delta points and two core points, but only one core point (the one on the upper side) is taken into consideration. A composite or accidental pattern cannot be classified into any one of these defined pattern classes. Quite often, it is a mix of one or more of the patterns classes and sometimes it may be a combination of a part of one or more of the classes. In addition, there are also minor variations from the classification scheme described.

WAYS OF CAPTURING FINGERPRINTS

Fingerprints are obtained in different ways. Figure 3 shows pictures of such fingerprints. The *rolled print* or full print is an FP obtained from a person by rolling the top phalange of a finger bulb onto a flat sheet of paper. This can also be viewed as laying out a semicylindrical surface on a plane. The *plain prints* are obtained by plain impressions of fingers without rolling. The *chance print* is obtained at the scene of crime, where it is left by chance (not intentionally). A chance print is usually a partial print and is generally of poor quality. It is also called a latent print or a mark.

Generally, rolled prints are used to identify a suspect. Chance prints are used to identify person(s) involved in a particular crime. Plain prints are used to check the sequence of ten prints taken in order on a ten-print slip (card) and are generally not employed for identification. Figure 2 shows sample fingerprints of different types.

EARLY MANUAL PROCEDURES

The early history of fingerprints is not known exactly. Credit for the first major scientific contribution goes to Francis Galton (1822–1916), who established the fact that no two fingerprints are alike and classified the patterns into three major classes for filing purposes. In addition to providing types and nomenclature, he discussed the all-important question of persistence. He proved that the details of the ridges constituting the patterns of finger impressions persist throughout a person's whole life. The patterns found on the fingers of a newborn infant are traceable on the fingers of the same person in old age and apparently effaceable only after death decay sets in. Edward Henry (1) introduced a more advanced classification of FPs, which is most widely used by law enforcement agencies and is known as the *Henry classification.* This method is based on the use of all ten fingerprints and is also called the "ten-digit (print) system." This method requires all ten digits for filing and identification. Harry Battley (2) proposed the "single-digit" classification system which uses only one print compared to the ten prints required by the Henry classification and is called a "single-digit system." This method is employed for chance print (latent print) identification in the manual system.

The Henry Classification

When all ten FPs of a person are available, the Henry classification (1) system is generally used. In this case, when a search is carried out against the ten-digit (print) collection, it is called a "ten-digit" search. The basic patterns used in this system of classification are loops (with subclasses left loop and right loop), whorls (clockwise, anticlockwise, and others), arches (plain and tented arches), and others. Further subclassification based on ridge count between the core point and delta point(s), if available, is also used to reduce the search.

Whenever a ten-print slip is received for identification, the Henry classification number is determined by an FP expert

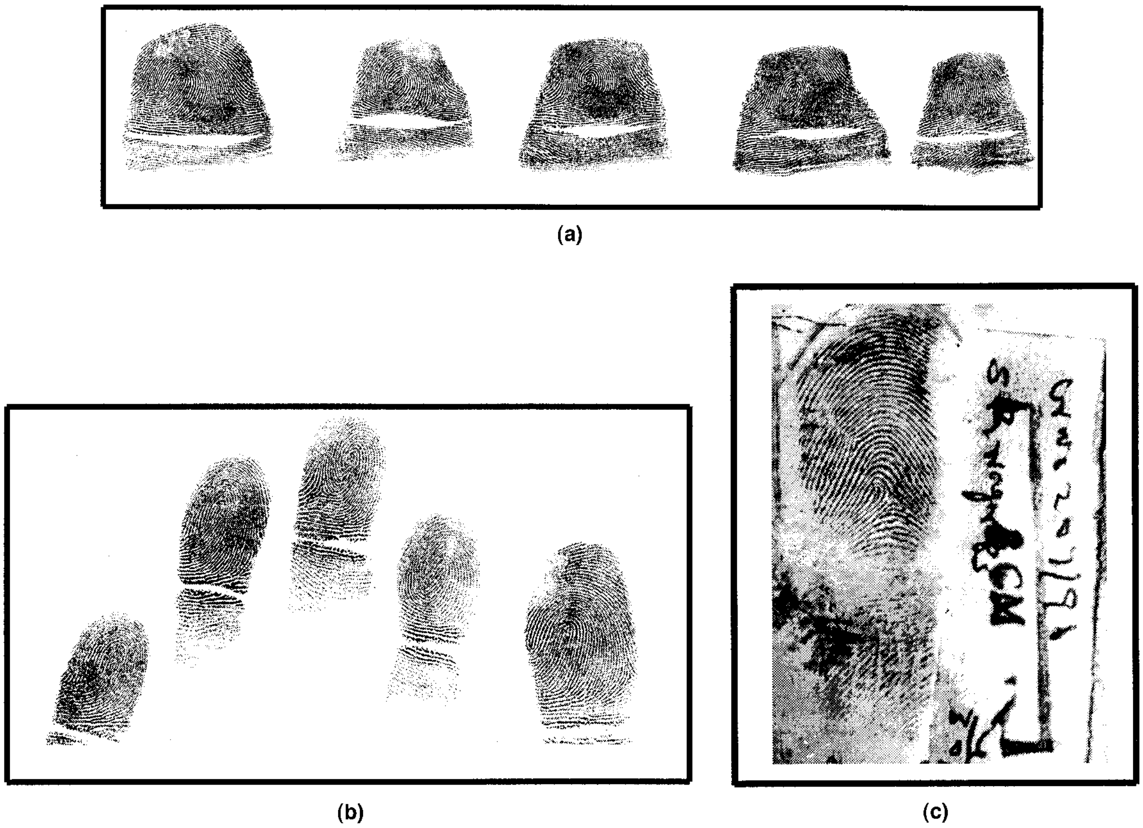


Figure 3. Pictures showing fingerprints obtained in different ways: (a) rolled prints; (b) plain prints; and (c) chance print.

by examining all ten print patterns. Then a search is made against the slips with the same classification number.

Battley Classification

Battley classification (2) is used when a single or partial print is available for identification. In this case the search is carried out against a collection of all individual digits (prints) and is called a "single-digit search."

Features Used in Manual Procedures

Comparison of FPs belonging to the same class is carried out on the basis of minutiae features. Following is the list of some of the minutiae types used in the manual procedure:

- Ridge end (also called ridge start or termination point)
- Ridge branch (also called merge or bifurcation point)
- Island
- Short ridge
- Cross
- Dot
- Fork
- Trifurcation

Limitations of Manual Procedures

Manual procedures in practice for a long period have become ineffective for the following reasons:

- Difficulty in handling a large volume of FP slips
- Deterioration of paper slips used for fingerprinting
- Long time required for identification
- Very low rate of positive identification
- Increasing loads of fingerprint identification

These limitations have made manual procedures (system) ineffective, although the need and use of FPs for investigation and authentication is ever increasing. This has led to an extensive research effort to automate the process using state-of-the-art technology.

Advances in computer technology can be used to advantage to mitigate the problems of the manual system by automating or semiautomating FP identification procedures. The relevant advances of importance for fingerprint identification systems are digital image processing principles, pattern recognition techniques, coupled with the availability of suitable hardware like high-resolution scanners and displays, cheaper memories, and high speed processors.

FINGERPRINT REPRESENTATION

A fingerprint is represented by its visible impression on paper, usually inked. Latent images of fingerprints are formed when fingers touch the surfaces of objects. They are made visible by dusting and special illumination. For computer processing of fingerprints, inked impressions of fingerprints are captured by digital scanners or cameras. A digital scanner scans a fingerprint slip and generates a digital image, an equivalent of a fingerprint impression on paper, for computer processing of the fingerprint. Recently some inkless sensors for capturing fingerprint impressions are reported.

The process of converting a fingerprint impression on paper into a digital image is called digitization. Two factors to be considered when digitizing are spatial resolution and brightness resolution. Spatial resolution is the number of samples chosen per unit length of space. Usually, this is expressed in dots per inch or dots per millimeter. The brightness resolution (or gray-scale resolution) is the range of brightness values for each pixel. Typically, for fingerprint digitization, eight bits per pixel are used to represent brightness values of pixels.

A digital image obtained from a scanner consists of a two-dimensional array. Each element of the array is called a pixel or picture element. The value of each pixel indicates the brightness at that point. In an eight-bit black and white scanner, the range of brightness ranges from 0 to 255. The 0 value indicates black and 255 white. The in-between values for a pixel indicate various shades of gray.

EARLY RESEARCH EFFORTS

The need for automatic fingerprint identification has attracted many people and companies to conduct research in this area. A few of these techniques are mentioned here. Trauring (3) proposed registering the relative locations of ridge and valley endings of some portions of the pattern. Kingston (4) suggested a semiautomatic system because of the tedious classification scheme and the amount of time required for manually processing each pattern. Wegstein and Raferty (5) considered several descriptors, such as ridge endings, bifurcations, enclosures, and some others, for describing the fingerprint impressions. The approach was based on matching a constellation (or group) of minutiae formed around a particular minutia. A discrimination (or score) matrix containing the percentage misses and false matches was used to evaluate the performance of the matching algorithm. This scheme is very sensitive to rotation of the print. Shelman (6) also selected the ridge endings and slope as the descriptors. However, his prime goal was to classify the patterns into several equally large groups to minimize the search time of the recognizer.

At Calspan (7), in addition to concentrating on fingerprint readers, extraction of minutiae locations, and ridge directions, a tremendous effort was devoted to designing an efficient reader and on-line data display for fingerprint patterns. The Calspan system processes the patterns in five steps: digitizing the pattern; removing the gaps and blots and producing the binary fingerprint image; preprocessing; minutiae detection; and postediting the patterns. Maram (8) and Horvath et al. (9) attempted to use optical techniques to identify fingerprints. Maram attempted to match the Fourier transform and the cross-correlation of patterns. The technique provides all of the details of the pattern. However, the numerous matching filters required and the slow process are drawbacks. The holographic technique is also a slow process and requires numerous filters. However, the optical techniques generally have the advantage of translational and rotational invariance.

Grasselli (10) was the first to advocate the linguistic approach in fingerprint identification. He suggested subdividing the pattern into "sample" squares, each containing the direction of the predominant slope of the ridge passing through it. He did not suggest, however, any formal grammar to describe the structure of fingerprint patterns. He proposed a classification based on the number of deltas (triradii, in his words). If the number of deltas is 0, 1, and 2, then the pattern is classified as belonging to arch, loop, or whorl pattern, respectively. The number of classes obtained by this approach is not sufficient for large file systems.

Hankly and Tou (11) did not formulate any form of language. However, their topological encoding scheme of fingerprint patterns has an implicit context-free language structure. With this technique, it appears that a great deal of information has been lost from data compression, on the basis of the redundancy assumptions among the ridges, which may lead to ambiguous description of the patterns.

Moayer and Fu (12) suggested a multilevel classifier using a syntactic approach for fingerprint-pattern recognition. The first-level classifier divides the fingerprints into seven classes using context-free grammars. The second-level classifier, using a stochastic language approach, further divides these seven classes into 39 classes. Finally, a tree system approach is used to generate a large number of classes. This classification is an improvement over the Henry system of classification. However, the authors concluded that for practical use still more investigation is required.

Malleshwar Rao (13) proposed a method for fingerprint classification based on minutiae features. He assumed the binary image of fingerprint as input. He used Deutch's thinning algorithm after smoothing the binary image of the fingerprint. He suggested two methods of extracting the features, like forks, bends, and ridge ends, from the thinned image of the fingerprint.

Kameshwar Rao et al. (14) suggested a syntactic approach for classifying fingerprints. They proposed a two-step procedure consisting of type classification and fine classification. Type classification is based on the global structure, and fine classification is based on minutiae in a small area around the core point. The core point is entered manually. Fingerprints are classified into nine types. In fine classification, features, such as forks, ridge ends, ridge bends (sharp change in slope), and ridge counts from the core to the features, are used for further classification.

The Automatic Fingerprint Identification System, operational at the Federal Bureau of Investigation (FBI) (15), was developed jointly over a period of 15 years by the FBI, the National Bureau of Standards, and the Rockwell International Corp., Pittsburgh, PA, among others. In the system the fingerprints are first fed to a reader which provides a list of minutiae points, including location and orientation. The classification of the fingerprints according to the pattern type is done manually. The classification data together with other information on the suspect, such as sex, age, and height, are fed into a general-purpose computer, which retrieves the fingerprint images that fit the suspect's description. Once the data of fingerprint classification and suspect information are sent to the main supervisory computer and candidate fingerprints are retrieved from the database, the suspect's prints and the file prints are matched.

Mehtre (16) observed that automatic detection of minutiae features from fingerprint images is more important than automatic detection of pattern classes because the former is more time-consuming for human experts whereas the latter is easy for experts and does not take any appreciable time. Hence, he focused his work on developing better methods for feature extraction. He developed a scheme of preprocessing and feature extraction of fingerprint images suitable for computer-based fingerprint identification.

Fingerprint Systems

Commercially available automated fingerprint identification systems (AFIS), are called fingerprint systems for short. There are a couple of such systems available from different vendors. Some are mentioned here. All of these systems are based on minutiae features for fingerprint matching and identification. However, there are some minor variations in the minutiae attributes and the degree of manual intervention.

De La Rue Printrak's (USA) automated fingerprint identification system (17) uses the minutiae data consisting of the location and orientation of fingerprint ridges at the points of terminations (ridge endings) or branches into two ridges (bifurcations). In this system, editing of automatically encoded marginal quality fingerprints is required. The system provides a listing of search respondents in order of decreasing probability of match. Printrak has announced an improved version called ORION, which automatically classifies a fingerprint pattern into one of nine classes.

Nippon Electric Company's (NEC) (Japan) automated fingerprint identification system (18) uses the following attributes of minutiae for identification. They are minutiae position represented by (x, y) coordinates, ridge direction, and topological relationship represented by counts of ridges between a minutia and its four nearest neighboring minutiae.

CIMSA's (France) Digidata system (19) uses the following attributes of minutiae: position, ridge direction, type of minutiae (ridge end or branch), and a quality factor (representing the confidence factor or reliability) associated with each feature used.

CMC's (India) automatic fingerprint identification system (20) is called FACTS, which stands for Fingerprint Analysis and Criminal Tracing System. It uses features similar to NEC's system, but it uses five nearest neighbors instead of the four nearest neighbors used in the NEC system.

AUTOMATIC FINGERPRINT IDENTIFICATION SYSTEM

Figure 4 shows a block schematic of an automatic fingerprint identification system. The term "automatic" here refers to the use of computers. Most often, it is meant as semiautomatic, that is, the so called automatic fingerprint identification systems (abbreviated as AFIS) do need human intervention to do fingerprint identification. Of course, most of the laborious and mechanical work is carried out by computers, and some tricky and decision making tasks are carried out by human beings who are expert in fingerprint identification.

Automatic fingerprint identification is arrived at using pattern recognition principles (24). The recognition of FP patterns is based on specific features (which are derived from a fingerprint image) and not just simple image-to-image matching. A set of features which uniquely represents a pattern is called the characteristic features. A set of characteristic features is called the pattern signature. The scheme of identification consists of feature selection, feature extraction, and feature matching.

Whenever a given pattern is to be identified, its features are extracted and matched against the features (of the pattern) stored in the database. The given pattern is considered to be that pattern (or that set of patterns) with which it matches most. In our case, the patterns are individual FPs. The characteristic features are the ridge characteristics or the "minutiae."

In automatic fingerprint systems the type of minutiae used are the ridge ends (terminations) and ridge bifurcations (branching, merging points). Other types of minutiae used in the manual system, like islands and short ridges, are also covered indirectly because an island can be considered a pair of bifurcating points and a short ridge can be considered a pair of end points.

Computer systems use ridge ends and bifurcation-point minutiae because end points and bifurcation points are the most widely available points compared with the others. A survey by Chatterjee (21) revealed that in a sample set of 1000, the frequency of occurrence of different minutiae is as follows: end points 77%, bifurcation points 20.6%, and others 2.4%. In a study at the FBI (7), it was recommended that computerized fingerprint identification may be based on the ridge endings and ridge bifurcation (minutiae), which are unique and are amenable to computerization.

A fingerprint image is captured through an input subsystem, which consists of a scanner or a frame grabber (CCD) camera. The output of an input subsystem is a digital image. The resolution used in fingerprint identification is typically 512 dpi (dots per inch). Such a high resolution is required to distinguish the ridges from valleys.

The digital image acquired through input goes through a preprocessing stage wherein various imperfections or degradations of the image are corrected. The preprocessing output

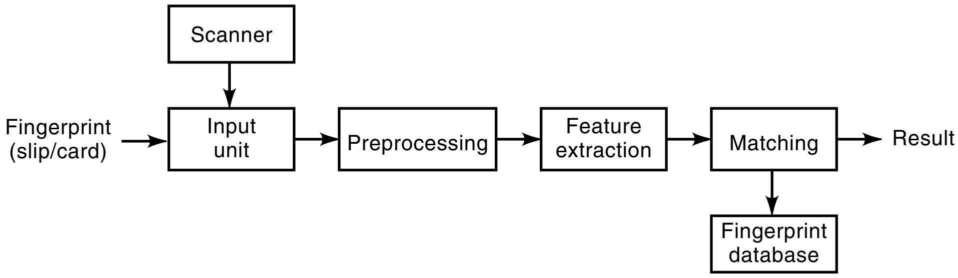


Figure 4. A block schematic of an Automatic Fingerprint Identification System.

is a nice, clean, and good quality image. This image is used for feature extraction of an input fingerprint image.

As discussed earlier, the ridge characteristic features, the minutiae, are extracted. Two types of minutiae, the ridge endings or termination point and ridge branching points or bifurcations, are identified at this stage.

A fingerprint database is a collection of fingerprint features. The database stores or contains information relating to each fingerprint along with its identification number and all of the features. This includes the original fingerprint image along with personal details.

When a query fingerprint is presented for identification, it is scanned and its features are extracted and matched against those in the database. The result of fingerprint matching is a ranked shortlist of likely fingerprints, which closely resemble the query (or search) fingerprint.

The final decision on the correctness of the match is made by a human fingerprint expert. The query fingerprint and the shortlisted fingerprint images are used by an expert to make the final decision on the correctness of the match. Thus, AFIS is an aid to fingerprint experts and not a substitute. It helps them in reducing the laborious task of searching from millions of slips to a couple of slips. This drastically improves the effectiveness of the task and improves accuracy and speed.

Preprocessing of Fingerprint Images

The output of a scanner (captured through the input unit) is a digital image of a fingerprint impression on paper. A digital image (typically rectangular) consists of tiny points called pixels or picture elements. If the value of each pixel is two valued (typical 0 and 1), then the image is called a binary image. On the other hand, if the pixel values range between 0 and a maximum value (typically 255), the image is called a gray image. The scanned image of a fingerprint is typically a gray image. Such an image is subjected to a series of image processing operations before it is used for feature extraction. The processing of an image before feature extraction is called preprocessing. The aim of preprocessing is to improve the quality of the input image and to reduce noise so that it becomes suitable for feature extraction. This also helps in reducing detection of spurious features and thus increases the accuracy of feature extraction.

Typically, preprocessing of a fingerprint image consists of ridge enhancement, thresholding, and thinning, in that order. Ridge enhancement is also called restoration of a fingerprint image, or simply restoration. Thresholding is an operation which converts a gray image (multiple values of gray) into a binary image. The binary image has only two values (black and white) for every pixel. In this case, the ridge-enhanced image is thresholded to get a binary image. The binary image is used for thinning. The thinning operation is also called skeletonization or medial-axis transformation. The thresholded (binary) image has thick ridgelines, which are reduced to single pixel-thick lines during thinning. The thinned image is used for extracting minutiae features. The exact steps used in preprocessing vary from one system to another. Quite often the details are proprietary and hence confidential. In addition, continuing research efforts aimed at improvement keep the details changing to some extent.

Fingerprint Image Enhancement and Restoration

Image-enhancement techniques improve the visual quality of images (like contrast improvement). Sometimes they also highlight some desired features and deemphasize undesired features of the image under consideration. However, image-enhancement techniques do not address any particular degradation in the image. On the other hand, image-restoration techniques use knowledge of degradation in the image and attempt to restore the (original) image quality. The ridgelines in the FP images have, generally, two types of degradations. One is that ridgelines are not continuous, and the other is that parallel ridges are not well separated. This is caused by poor inking and uneven pressure applied while taking the FP impressions. This, however, is not a problem for human experts. They ignore small breaks found in inked impressions and see them as continuous ridgelines. Similarly, the parallel lines, which are not well separated (cluttering noise connects parallel ridges), are also seen and considered parallel ridgelines. This adaptive visual perception of human experts has to be incorporated into automatic processing. Hence, in FP images two types of enhancements/restoration are desirable: to fill small breaks found in the natural ridge direction and to delete any link because of noise existing between otherwise parallel ridges. The topic of image restoration is discussed extensively in the literature (22,23). The restoration of fingerprint images is briefly discussed here.

One way of achieving ridge enhancement is by using directional filters. Directional filters are also called adaptive filters, context-sensitive filters, or contextual filters. These filters are designed to achieve the objectives previously described. Directional filters are similar to conventional digital filters (in spatial domain), but instead of using the same filter mask over the entire image, different filters are used in different regions of the image. In each region, a filter is selected depending on the local context. Because local ridge direction is used as the context for filtering, they are called directional filters.

Directional filtering consists of the following two steps:

- Computation of ridge directions
- Design of filters

Ridge Direction Computation. The ridge direction at a point (i, j) in the FP image is computed by the following equation (23):

$$D(i, j) = \text{Index of } \min_{D=1}^{N} \left\{ \left(\sum_{K=1}^{L} |G(i, j) - G(i_{\mathrm{k}}, j_{\mathrm{k}})| \right) \right\}$$

Where $D(i, j)$ is the ridge direction at point (i, j), $G(i, j)$ is the gray value at the point (i, j), and the $G(i_{\mathrm{k}}, j_{\mathrm{k}})$ is the gray value in the direction d. N is the number of directions used, K is the number of pixels used in each direction for computing direction. L is chosen so that it is more than the average width of ridgelines.

The image formed by the directional value at each point of pixel value, is called a pixelwise directional image. For directional filtering, block wise (or region wise) directions are required. These are computed from the pixelwise directional image as follows: In each block (region), the histogram of the pixelwise directional image is computed, and the block is assigned that direction which has the highest frequency of occurrence in that block. The image formed by the block directions is called a blockwise directional image.

Design of Filters. To design a digital filter in the spatial domain, two things have to be determined, namely, the filter size and the filter elements. The average ridge width can be taken as the size of the filter. The filter elements should be chosen so that the two types of effects are achieved. It is evident that the ridge direction is required for the restoration. The basic filter for one particular direction is designed, and filters for the other directions can be generated by rotating the basic filter (23). The angle of rotation and the number of different filters required depend on the number of directions used. The number of filters is equal to half the number of the directions used because horizontal is considered one direction, that is, the negative x-axis and the positive x-axis are not distinguished for the purpose of ridge enhancement.

The basic filter consists of a combination of two filter masks, one for filling ridge breaks and the other for separating contiguous parallel ridges. Suppose the filter size is $n \times n$. Then the filter weights for averaging (filling ridge breaks) in the direction of the ridge can be given as in Table 1(a). The weights should decrease from the center row on both sides. The effect of joining ridge lines is considered an averaging or integration along the ridge direction, and the weights taper off in the orthogonal direction of the ridgeline. The weights for separating the ridges can be as shown in Table 1(b). The weights should add up to zero in each column. The separation of ridges is considered differentiation across the ridge direction (i.e., perpendicular to the ridge direction). As the sum of weights is zero, it ensures that in constant gray level regions, the output of convolution is zero (the differentiation of a constant is zero). This means that the regions of constant gray level appear black, and only the regions of line segments are highlighted. To retain the white background as white after applying a directional filter, a one is added to the central weight of the filter.

Table 1. Filter Masks of Size 5 × 5 for Fingerprint Image Restoration

(a) Averaging filter

z	z	z	z	z
y	y	y	y	y
x	x	x	x	x
y	y	y	y	y
z	z	z	z	z

$x > y > z >= 0$

(b) Differentiating filter

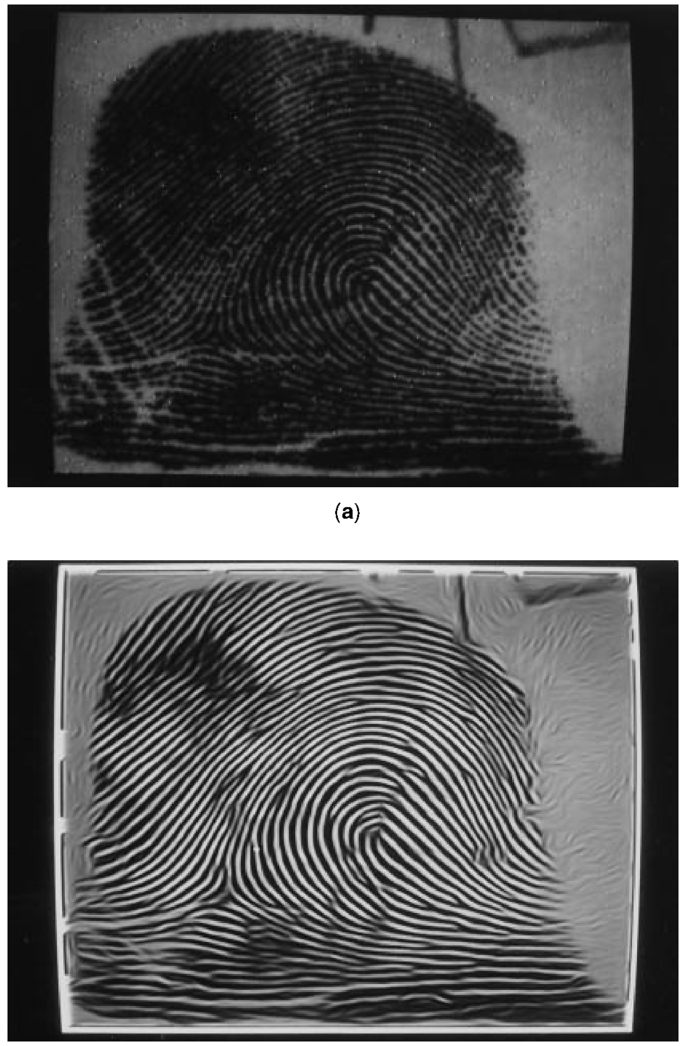
r	r	r	r	r
q	q	q	q	q
p	p	p	p	p
q	q	q	q	p
r	r	r	r	r

$p + 2q + 2r = 0$

(c) Combined filter

m	m	m	m	m
l	l	l	l	l
k	k	k	k	k
l	l	l	l	l
m	m	m	m	m

$k = x + p$, $1 = y + q$, and $m = z + r$



(**a**)

(**b**)

Figure 5. Picture showing restoration of fingerprint image: (a) image before restoration; (b) image after restoration.

The effect of joining in the ridge direction and separating in the orthogonal direction can be achieved by using both filters together. The combined filter is given by the sum of these two filters; see Table 1(c). To normalize the filter, each element of the combined filter is divided by the sum of filter weights. It is found that if the filter weights at the corners are nonzero, the filters in all directions are not the same because of truncation of weights that are in the corners of the basic filter. For symmetry and an equivalent effect in all directions, it is desirable that the corner weights are either rounded off to zero or are close to zero so that their effects are negligible.

Figure 5 shows the restoration of a sample fingerprint image. Figure 5(a) shows an input image and Fig. 5(b) shows the ridge-enhanced and the restored image. It is clear from these images that the ridge breaks in the original image have been filled up in the restored image. Similarly, the cluttered ridges have been well separated, thus, restoring the degraded (smudged) image quality.

FEATURE EXTRACTION

Two types of features are detected in FP patterns, namely, high-level (or global) features and low-level (or local) features. The high-level features include the pattern class, the core and delta regions (points), and the phalangial crease. The number of core and delta regions (or points) characterizes an FP pattern class. For example, a loop pattern has a core and a delta. A whorl has a core and two deltas, and an arch has neither core nor delta. The low-level features are the minutiae points, which characterize a fingerprint pattern uniquely. The recognition or identification of a FP is based on matching the minutiae features, and the matching is restricted to the FPs of the same pattern class.

Detection of High-Level Features

In the following sections we discuss detecting various high-level features, namely, the pattern class, the phalangial crease, and the core and delta regions. Quite often automatic detection of these features is not accurate, especially if the fingerprint image is of poor quality. Chance prints are usually poor quality prints. Hence, fingerprint systems provide a user interface for user interaction and verification of these features by the user.

The Pattern Class. Human fingerprint experts classify fingerprint patterns into many classes based on the ridge flow patterns. In automated fingerprint systems, a similar analogy is also used for pattern class identification. The ridge direction information is computed from a given image and is analyzed to classify into various classes, like left loop, right loop, whorl, and arch. Singular points (the core and delta points) are also used to confirm the pattern class detected. For example, a whorl pattern has a core point and two deltas, one each on the left and right sides of the core point. Similarly, an arch pattern has neither a core nor a delta.

The Phalangial Crease. A FP image means the image obtained from the digitization of the impression of the top phalange of a finger. At the time the impression is taken, quite often the crease line (folding line) between the top phalange and middle phalange of the finger also comes in. For identification purposes, the image area is restricted to the image corresponding to the impression of the top phalange. The impression of the crease line results in a blank area, generally toward the bottom of the image. This property can be used to detect it automatically. If the crease line exists in the input image, it is detected and the area below the crease line is ignored for further processing.

The Core and Delta Regions. These are indicated by core point and delta point(s). These are either detected automatically or entered manually by fingerprint experts. In some systems, these points are detected automatically and verified by fingerprint experts before they are used in the identification process.

Low-Level Features

The ridge characteristics are called low-level features of which there are two types, the ridge ending (terminations) and ridge branching (merging), collectively called the minutiae. These points are extracted from the FP skeleton image, which represents the center-lines of ridges.

Attributes of a Minutia. A minutia is characterized by the following attributes:

1. *Minutia Position.* This is represented by the (x, y) coordinates in the FP image space. The top left corner of the image is taken as the origin (0, 0). The top row of the image is the x-axis, and the leftmost column is the y-axis. Thus, the point of maximum x and y coordinates is the bottom right corner point.
2. *Minutia Direction.* Minutia direction is the direction of the local ridge at the point of minutia. For computing the ridge direction, the ridge is traced from the minutiae position along the ridge up to a certain length. Then the direction is computed using coordinates of these two points, i.e., the minutiae coordinates and the last traced point at a certain length on the ridge.

   For a bifurcating point, all three ridges emanating from it are traced, and the corresponding angles are computed. The direction of the bifurcating point is along the emerging bisector of smallest angle where three ridges meet.
3. *Minutia Relationship.* Minutia relationship is the set of ridge counts from a given minutia to its neighboring minutiae. For a given minutia, some fixed number of nearest neighbors minutiae are taken and the corresponding intervening ridge counts are taken as the minutia relationship. The number of neighbors chosen varies from one system to another. Typically, it is four to five.

Extraction of Minutiae

The minutiae are the ridge endings (i.e., ends/starting points) or ridge bifurcation (branching/merging point). It is conceptually and computationally simple to detect the minutiae features from the FP skeleton image. The FP skeleton image represents the centerlines of FP ridges, which are one pixel wide. The following definitions are useful for detecting minutiae.

Crossing Number. The crossing number is a useful criterion for extracting minutiae features from thinned images. The crossing number (CN) at a point X, (where $X = 1$) is defined as follows:

$$\mathrm{CN} = \left(\frac{1}{2}\right)\sum_{i=1}^{8}|P(i) - P(i+1)|$$

Here i has a period of 8, that is $P(9) = P(1)$, and $P(i) = (0, 1)$. The 3×3 neighborhood used for computing a crossing number is illustrated in Fig. 6.

The crossing number has some useful properties, and these are detailed in Table 2.

$P4$	$P3$	$P2$
$P5$	X	$P1$
$P6$	$P7$	$P8$

Figure 6. A 3×3 neighborhood around a point X.

Table 2. Properties of the Crossing Number

Crossing Number	Property
0	Isolated point
1	End/start point
2	Connecting point
3	Branch/merge point
4	Junction point

Detection of End Points. Any point P in the discrete plane with only one neighbor is called an end point. Alternatively, any point with CN equal to 1 is an end point. The end point as defined in a 3×3 neighborhood is shown in Fig. 7.

Detection of Bifurcating Points. Intuitively a bifurcating point can be thought of as a point with three neighbors. However, this may not be true always. Some example neighborhoods are shown in Fig. 8, which have three neighboring points but are not valid bifurcation points.

A point with three neighbors and CN equal to three is a valid bifurcating point. This rule is used for extracting the bifurcating points. Figure 9 illustrates some examples of valid bifurcation-point neighborhoods.

Postprocessing and Noise Cleaning

The initial set of minutiae detected contains a large number of spurious minutiae. The aim of postprocessing and noise cleaning is to validate the genuine minutiae and eliminate the false and spurious minutiae. To optimize computation time, only the end points are detected first, and the cleaning operation is carried out to scrutinize them.

Spurious End Points. The end points are tested one by one for validity. The ridge is tracked from end points. A ridgeline is characterized by a sequence of ones. The tracking is done to a certain fixed length (number of pixels) of the ridge. This length should be on the order of the “short ridge” length. If the tracking is successful, that is, the ridge exists for a length longer than a short ridge, then the end point is taken as a correct end point. If the ridge ends before tracking the fixed number of pixels, then the end point is spurious. In this case, both the end points and the short ridge segments are deleted. During tracking, if a bifurcating point is encountered and the ridge length from the end point is short, then the ridge up to the bifurcating point is deleted. The corresponding end point minutia is deleted. This is repeated for all of the minutiae. In this process, many minutiae, which are spurious, are eliminated. On an average, more than 60% of the minutiae detected initially are false and are removed in this process.

Spurious Bifurcating Points. After eliminating spurious end points, then the skeleton image is scanned to detect bifurcating points. All the points qualifying as bifurcating points are detected. As with the end points, not all of the bifurcation points are correct. To detect the spurious ones, bifurcating points are tested one by one for validity. A bifurcating point has three ridge segments starting from it. Each of these segments is traced and checked to see whether it is sufficiently long. If any of the segments is shorter than a prespecified length, then the bifurcating point is spurious.

Joining Ridge Breaks. Any break in a (otherwise continuous) ridge gives rise to two end point minutiae with opposite (or nearly opposite) directions. Such a minutiae pair is called a minutiae couple and is to be deleted. In addition, the ridge break is filled by connecting the two end points by a generated ridgeline.

0	0	0
0	P	1
0	0	0

Figure 7. The neighborhood of an end point P.

0	1	1
0	1	0
1	0	0

(**a**)

0	0	1
1	1	1
0	0	0

(**b**)

0	0	1
0	1	0
1	1	0

(**c**)

Figure 8. Three examples of invalid bifurcating-point neighborhoods.

1	0	1
0	1	0
1	0	0

(**a**)

0	0	1
1	1	0
0	1	0

(**b**)

0	0	1
0	1	0
1	0	1

(**c**)

Figure 9. Three examples of valid bifurcating-point neighborhoods.

Figure 10. Picture showing the minutiae features of a fingerprint image. Arrows in color represent the minutiae features. The arrowhead location indicates the minutia position, and the direction of the arrow indicates the minutia direction.

Discarding Border Minutiae. The minutiae detected along the border of the FP image are not valid minutiae and are deleted.

Figure 10 shows a fingerprint image with its minutiae detected by a fingerprint system. The arrows in color shown in the fingerprint image are the minutiae features. The arrowhead shows the minutia position and the arrow direction shows the minutiae direction.

FINGERPRINT MATCHING

Fingerprint identification is carried out by matching fingerprint features (the minutiae), not by matching images. The terms recognition and identification are used synonymously. The recognition of FPs applies to an automated collection of fingerprint records, that is, fingerprint images and their features are stored in a database. When a test or search FP is received for identification, the matching process is applied to identify some of the database prints that closely resemble the search fingerprint. A query fingerprint resembles a database print if the minutiae features of the query print are within specified tolerance limits. The outcome of this process is a ranked shortlist along with their "matching scores." Final identification is confirmed by a human fingerprint expert. If no database print is within the specified tolerances, then the outcome is, "no matching print for the query print." Most of the practical fingerprint systems are robust enough, and one does not encounter a case where a matching database print exists, and the system declares otherwise.

The following are two types of matching measures:

1. Dissimilarity (mismatch) measure
2. Similarity (matching) measure

Dissimilarity Measure

For a given pair of fingerprint images, the dissimilarity measure, also called the mismatch function, is given by the following equation:

$$M = W_1 * \sum |D_{i,j}| + W_2 * \sum |d_{i,j}| + W_3 * \sum |T_{i,j}| + W_4 * \sum |R_{ij}|$$

where M is the mismatch function, W_1, W_2, W_3, W_4 are constants, $D_{i,j}$ is the difference of distances, $d_{i,j}$ is the difference of directions, $T_{i,j}$ is the difference of minutiae types, and $R_{i,j}$ is the difference of minutiae relationships. The summation is computed over all the minutiae present in both prints under consideration.

The type information is given a low weight, as it is quite possible that an end point in one print may appear as a bifurcating point in another instance or vice versa. This can happen because of different pressures applied at the time the impressions were taken or during the ridge enhancement and restoration. This function is computed against the test fingerprint for all FPs. The mismatch scores are sorted in ascending order. The top few prints in the list are given to the expert for final decision as the most likely.

Similarity Measure

A matching function based on similarity measure can be given as follows:

$$S = \sqrt{[P^2/(M^*N)]}$$

Where S is the similarity measure between a given pair of prints, M is the number of minutiae in the test print, N is the number of minutiae in the reference print, and P is the number of pairing minutiae.

A minutia in the test print is said to be paired with a minutiae in the reference print if all the attributes of the minutiae pair are within a specified tolerance, that is, the difference of positions, the difference of directions, and the sum of the differences in minutiae relationships are within some specified limits.

Types of Matching

In a fingerprint system there are two types of fingerprint collections (or databases), namely, the collection of rolled fingerprints (or prints) and the collection of chance prints (or marks). The fingerprint identification queries are also of two types, the rolled print identification and the chance print identification. Queries of one type can be applied to databases of the other type. Based on these requirements, there are four different types of matching methods provided in a fingerprint system. They are print-to-print, mark-to-print, mark-to-mark, and print-to-mark. These are described following.

Print-to-Print. This is also called a ten-print search. When a suspect or a person is to be identified, the rolled fingerprints of the person are taken and matched against the rolled fingerprint database. Such matching is used for personal identification.

Mark-to-Print. If a chance print found at a scene of crime is to be identified, the chance print (or sequence of chance prints) is matched against the ten-print collection. This is called chance print identification.

Mark-to-Mark. If a chance print is not identified, it is searched against the collection of unsolved chance prints. If a match is found, it indicates that the same person is related to other crimes, which are also to be solved.

Print-to-Mark. When the result of print-to-print matching yields no positive result, then the print is subjected to print-to-mark matching. In this type of matching, the rolled fingerprints of the arrested (suspect) person are matched against the collection of unsolved chance prints. If a correct match is found, then it proves that the person under arrest is responsible for all of the crimes, which corresponds to the chance prints that match.

APPLICATIONS OF FINGERPRINT IDENTIFICATION

Fingerprints are used for personal identification. Fingerprints are better for positive identification of a person compared to other means of identification like signature, face etc. Personal identification is an essential factor in many applications. Such applications include criminal tracing, social security benefits, issue of driving licences, "no criminal background" certificates, passports, access controls, citizen (voter) identity cards, pension benefits, and resolving disputed documents. Some of these are briefly discussed here.

Criminal Tracing

Police departments all over the world maintain fingerprint records of all convicted persons (criminals). This record called fingerprint slip (or card) contains fingerprint impressions of the person, personal particulars, like name, sex, age, and address, and details of conviction. The collection of such fingerprint records is searched when a suspect is to be identified. Quite often, suspected criminals use different and false names. Use of fingerprints for identification brings out their real identities and provides an objective basis for enhanced punishment for repeat criminals, as required by law. Also, fingerprints captured from the scene of the crime have great value in identifying criminals.

Citizen (Voter) Identification Card

The authorities (or agencies) who issue identity cards (municipalities, employers, institutes, road transport authorities, passport offices, etc.) have to make sure that only one identity card is issued to genuine candidates. If by mistake duplicate cards are issued or forged, there must be a quick and effective method for identifying duplicates. This can be achieved with fingerprint-based identification.

CONCLUSION

In this article, basic concepts related to fingerprints and fingerprint identification are described. A brief survey of literature on manual procedures, research efforts toward automation of fingerprint identification, and some operational systems for computer-based fingerprint identification are covered. The "automatic fingerprint identification systems" are in effect semiautomatic systems, that is, the decision of fingerprint identification is not entirely automatic. It involves intervention by human fingerprint experts. The degree of intervention may vary from one system to another, but it is there nevertheless. However, this is not to understate the importance of computer-based systems. A computer-based fingerprint identification system helps human fingerprint experts in reducing search time drastically without missing any likely fingerprints. This makes their job very effective, reliable, and fast. Thus, it helps them to arrive easily at a final decision on the correctness of a match. It has been found that because of the use of computers in this work, the rate of positive identification has significantly increased, compared to manual procedures.

A fingerprint image obtained from a digital scanner (or camera) is subjected to various image processing operations to improve image quality and to minimize degradations that have crept into the input image. Typical preprocessing steps include ridge enhancements (image restoration), thresholding, and thinning. A generic scheme of directional filtering for fingerprint image restoration is described. An intermediate image, "directional image," is computed from the input fingerprint image. This is useful for identifying high-level features like core and delta regions and the pattern class of the fingerprint.

The preprocessed image is used to extract fingerprint minutiae features. A set of minutiae features constitutes the characteristic feature of the fingerprint, and this is unique for every fingerprint. In many countries a minimum of eight minutiae is considered necessary to establish positive identification, whereas some others consider a minimum of 15 minutiae necessary. All the minutiae features extracted from a fingerprint image along with other details like fingerprint image and a unique serial number, etc., are stored in the fingerprint database. Quite often, personal attributes are stored in a separate database.

To identify a query fingerprint, minutiae-based matching is carried out to determine (automatically) the most likely list of fingerprints from the database. The final decision is made by human experts by comparing the query print and the shortlisted prints.

Fingerprints are used in many applications where some sort of personal identification is involved.

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B. M. Mehtre
CMC Ltd.