# Fingerprint Minutiae: A Constructive Definition

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**Abstract.** The flow pattern of ridges in a fingerprint is unique to the person in that no two people with the same fingerprints have yet been found. Fingerprints have been in use in forensic applications for many years and, more recently, in computer-automated identification and authentication. For automated fingerprint image matching, a machine representation of a fingerprint image is often a set of minutiae in the print; a minimal, but fundamental, representation is just a set of ridge endings and bifurcations. Oddly, however, after all the years of using minutiae, a precise definition of minutiae has never been formulated. We provide a formal definition of a minutia based on the gray scale image. This definition is constructive, in that, given a minutia image, the minutia location and orientation can be uniquely determined.

## 1 Fingerprints

Positive person identification and authentication are important in our fast-moving, modern society with the infrastructure of airline travel and broadband networks. Traditional identification methods such as driver's license, passport, ATM cards and PIN codes do not meet the demands of this wide-scale connectivity. Automated biometrics in general, and automated fingerprint authentication in particular, provide efficient solutions to these modern identification problems.

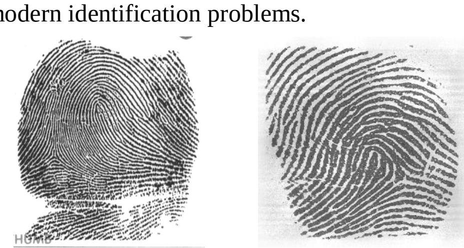

**Fig. 1** Rolled inked fingerprint (left), fingerprint acquired with CMOS sensor (right).

For many years, fingerprint acquisition has been accomplished by first imprinting an inked finger on paper and then converting the image into machine-readable form (see Fig. 1). Recent developments in sensing technology have resulted in several inkless (often referred to as *livescan*) fingerprint scanners. Compared to the ink and paper-based methods practiced in law enforcement applications, this technology is easy to use. Frustrated total internal reflection and other optical methods [3] are the oldest livescan methods. The CMOS capacitative [4] sensors and other technologies made it possible to shrink the sensor size to the area of a postage stamp so that the sensors fit in laptops, cellphones and personal digital assistants. However, compared to rolled prints and ten-print cards, these sensors produce less information about a finger (Fig. 1).

Automatic identification of images of such small fingerprint portions requires complex algorithms similar to the algorithms used for conventional latent fingerprint identification using Batley's method [5]. In this method, as many as eighteen types of ridge features have been defined. Fortunately, these complex features can be considered as a combination of two fundamental features known as ridge endings and bifurcations (see Fig. 2). Together, these basic features are referred to as *minutiae*.

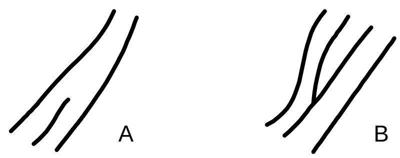


**Fig. 2** Ridge ending (A) and ridge bifurcation (B).

Commercial fingerprint authentication applications range from controlled access to private medical dossiers, networked financial transactions such as e-business and physical access into buildings. Consequently, many solutions from many vendors are available on the market. These solutions are often based on proprietary technology and algorithms and each has its own fingerprint representation (template format). With the progress of networking technology, there is a need now to make such systems interoperable to share data that have been acquired over the years. Large enterprises typically like to deal with multiple vendors of sensors and fingerprint matchers and hence individuals who have been enrolled on one sensor type should be able to authenticate themselves on a different sensor. Fingerprint authentication technology, which is not open, will limit its uses in these applications. Recently, there have been serious efforts to promote openness through public. One aspect is the ongoing work on a Common Minutia Exchange Format Template [1], based on minutiae. Minutiae have been used for many years in automated fingerprint matching. However, a precise definition of minutiae has never been formulated. Rather, minutiae have been loosely defined and extracted based on some kind of binary image obtained from a fingerprint image. For instance the NIST database [6] specifying minutia locations gives no definition of the locations given, but relies of the answers of an automated minutia-finding system with some correction by human experts. No precise definition for the location of expert-marked minutia was necessary because fingerprint experts do not rely on distance measures for their demonstrations of fingerprint similarity.

Because of vendor specific algorithms, the minutia points tend *not* to be located and oriented the same on the same image for the different vendors. This is due to possible differences in minutia definitions and the different image processing algorithms. However, when standards are defined, it is important that every concept in the standard is carefully defined. If needed, vendors can then compensate for biases in their extraction algorithms and different algorithms can be compared to a well-defined ground truth. In this paper, we present a definition of minutiae, which is based on the gray-scale profile of fingerprint images.

## 2 Fingerprint processing

The purpose of fingerprint image processing is to extract a condensed representation of the image. This representation (referred to as a template) is used for fingerprint matching. From the ridge flow pattern is extracted the minute detail that makes a fingerprint different from other prints. A first part of the detail that is usually used in fingerprint representations is the set of endings and ridge bifurcations in the flow pattern. Fig. 3 gives a portion of a fingerprint image. It shows a close-up of the flow pattern. We follow the convention (corresponding to the reality of inked cards and FTIR images) that ridges appear black and valleys between ridges are white, so A represents a ridge ending and B represents a bifurcation. We further follow the intuitive convention that ridges have high values and valleys have low values, although this leads us to have white pixels having low values and black pixels having high values.

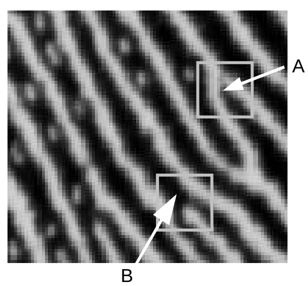


**Fig. 3** Ridge ending (A) and ridge bifurcation (B).

Note that the minutiae in Fig. 3 are of exceptional quality. In many cases, the presence of minutiae is much less clear-cut. Often, for example, it is difficult to distinguish between a ridge ending and a ridge bifurcation since differences in pressure while acquiring the fingerprint image can join a ridge ending to an adjacent ridge, producing a bifurcation and *vice versa*.

The minutia extraction process typically consists of ridge extraction, followed by ridge thinning and minutiae extraction. Ridge extraction, or ridge segmentation, is essentially the step of binarizing the fingerprint image. That is, somehow the fingerprint image $I:(x,y) \rightarrow [0,255]$ is converted to $B:(x,y) \rightarrow \{0,1\}$, where the value $0$ corresponds to valleys and $1$ to ridges. One way of accomplishing this is to select a global threshold $T$ and converting the image $I(x,y)$ to a binary image as

$$B(x,y) = \begin{cases} 1, & I(x,y) > T \\ 0, & I(x,y) \le T \end{cases}$$

Due to the poor quality of many fingerprint images, this approach is most often inadequate for extracting minutiae. In areas of the finger that are dry, no ridges may be detected, while in areas where the finger is wet, no valleys may be detected.

The typical solution is to use a threshold $T(x, y)$, which is a function of the spatial location. Virtually every published method of feature extraction (e.g., [2]) computes the orientation field of the fingerprint image, which reflects the local ridge direction at every pixel. Fig. 4 gives a simple description of this technique as it is applied in [2]. The local direction $p$ of the ridges is determined by computing gradients in small blocks and averaging these in larger image blocks. Now, consider an image block around a pixel and its projection parallel to the gradient direction onto the $q$ axis in Fig. 4. The projected profile is then of the form shown in Fig. 4b. The pixel along line $q$ that has maximum intensity value and a few pixels on either side are set to '1' (white) the remaining pixels are set to '0'.

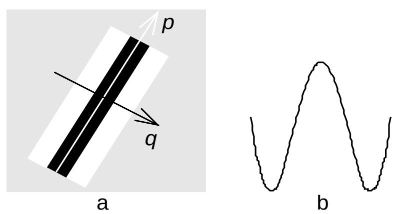


**Fig. 4 Local thresholding based on expected image function.**

At this point, a binary image has been computed which more or less faithfully represents the original image. The ridges will have width that will vary over the fingerprint images. The next processing steps are typically composed of a sequence of image operations: Directional smoothing, Thinning, Morphological filtering and Minutia pruning (post-processing). These types of operations may be performed in different order. What should be noted is that these steps are fairly *ad hoc* and that these processing steps may not have much to do with the underlying image function, $I(x, y)$.

Thinning, or skeletonization, (also the medial axis transform) is a notoriously difficult problem with many competing algorithms still being proposed. Skeletonization algorithms are very susceptible to noise or can generate skeletons that do not closely correspond to the intuitive idea of the skeleton.

## 3 Minutia definition

The sequential approach to fingerprint minutia extraction is more or less the state-of-the-art. It is purely a bottom-up process. Not much attention is given to modeling the image formation process or to modeling the object that is imaged (the finger).

One aspect of modeling a fingerprint is modeling the minutiae. Oddly enough, although fingerprint-based authentication and identification has been around for quite some time, a precise definition of minutiae has never been formulated. Often only a loose description of minutiae is given. Since we began this work, we have contributed to the AAMVA standard [7] which does adopt a minutia definition (paragraphs C.10.3.2,3) but this specifies points on the medial skeleton, itself subject to variations of implementation and presupposing a binary image which is also not well-defined.

There are very good reasons for formulating a precise definition of minutiae:

- The ground truth of minutiae, both ridge endings and ridge bifurcations, in a fingerprint image will be well defined for manual annotation.
- Automated minutia extraction algorithms can be compared.
- Automated extraction algorithms can be designed with sub-pixel accuracy.
- As stated in Section 1, vendors could compensate for biases in their minutia extraction algorithms and can construct templates that are more interoperable.
- A good model of a minutia will allow for the definition of a well-grounded quality measure that considers how well the data fits the model.

The location and orientation of minutiae could be defined based on the result of fingerprint image processing. Commonly, a pixel that has only one neighbor in the thinned image is said to be a ridge ending, while a pixel that has three neighbors is said to be a ridge bifurcation. Clearly, the location and orientation of the minutiae are greatly dependent on the various processing steps. For example, thresholding a ridge at half the ridge height, or close to the top of the ridge will affect the thinning and hence the final location of the ridge ending. In general, the minutia locations in image $I(x,y)$ should be equal to the locations in image with transformed intensities $g(I(x,y))$. Hence, the positions of minutiae should *not* be based on some ill-defined, nonlinear function (like thresholding) of the image function. That is, the positions should be calculated using the image function itself.

Fig. 5a shows an image of a ridge ending. A typical thinning operation would leave a ridge ending somewhere near $p_1$, but the actual location would vary depending on the actual shape of the ridge ending. Similarly, if a system worked by thinning white (valley) regions, the singular point in the skeleton would be near $p_2$. Other systems might mark the minutia at $p_3$. In this symmetrical, binary image, $p_3$ appears to be well-defined, but for a real minutia with arbitrary binarization, $p_3$ could also vary considerably.

In a way, asking where the ridge of a fingerprint ends is very much like asking, while walking off a mountain ridge in the direction parallel to the ridge, where the ridge ends and where the valley starts. This is depicted in Fig. 5b. Here one has to keep in mind that only local measurements of the mountain ridge can be made.

What we want to do is model the image function $I(x,y)$ of a minutia. The perpendicular cross-section of a ridge is very much like a portion of sinusoid as the function $W(x)$ in Fig. 6, while a parallel cross-section along the length of the ridge is a smooth step function $L(x)$ in Fig. 6. We model these functions as

$$L(y) = \frac{1}{1+e^{-y/\alpha}} \quad \text{and} \quad W(x) = \frac{1}{2}(1+\cos(\frac{2\pi x}{\beta}))$$

with the minutia function $m(x, y) = h\, L(y)\, W(x)$ defined for $-\beta / 2 \le x \le \beta / 2$.

Here *h* is the height of the ridges, $\alpha$ and $\beta$ are scale constants. In practice if the period of the ridge oscillations is $r$, then we choose $\beta = r$ and $\alpha = r / 10$. Here $r$ can be estimated globally or locally for the ridge in question.

When moving along the ridge in Fig. 5b in the direction $p$, one could define the ridge ending to be either the point where one starts descending or the point where one stops descending. Or with $I$ denoting the image function of the ridge, the point where the height starts changing, i.e., $p_1$ the first $p$ where $\partial I / \partial p < -\varepsilon$, or the point where the height stops changing again, i.e., $p_2$ the first $p$ where $\partial I / \partial p > -\varepsilon$.

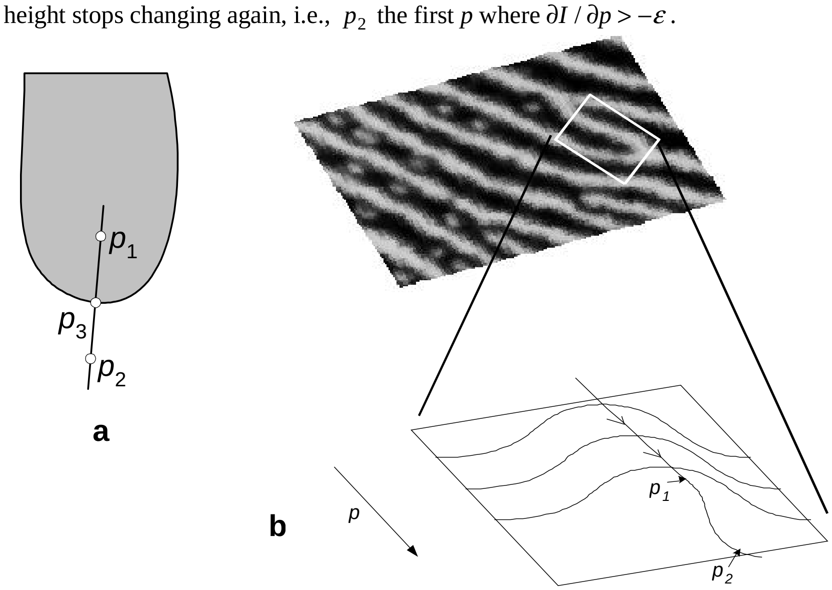


**Fig. 5** Possible locations of a minutia on the picture function of a ridge ending.

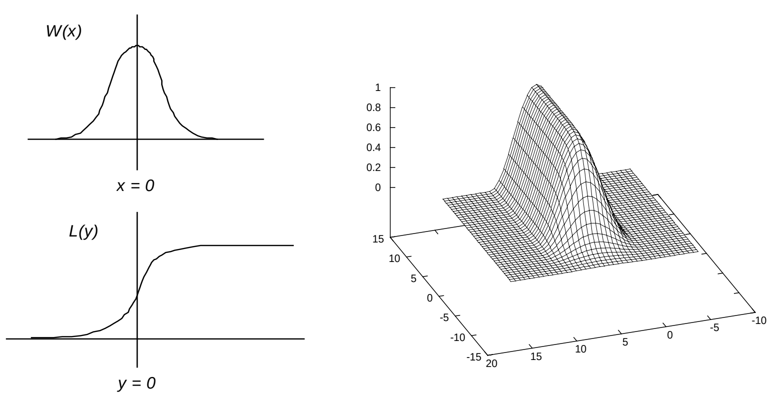


**Fig. 6** The ideal image function of a minutia.

Similarly, these points could be defined by relative heights. However, there are two obvious disadvantages to these choices:

- The definition involves an arbitrary constant $\varepsilon$.
- The location of these points change when smoothing operations are performed on the fingerprint images
- The exact location of the points is hard to determine.

Therefore, the point where the gradient $\partial I / \partial p$ is at a minimum (most negative), i.e. the point where

$$\partial^2 I / \partial p^2 = 0, \quad \text{hence } \partial^2 m / \partial p^2 = 0$$

is the obvious choice, i.e. *(x,y)=(0,0)* for our ideal minutia.

## 4 Minutia position estimation

In this section, we examine how well the function proposed in Section 2 fits minutiae. However, fitting the function $m(x, y)$ to the data is a difficult optimization problem. Therefore, as a first attempt, we estimate the parameters $h, \alpha$ and $\beta$ from data directly and then fit the minutia function. Least-squares estimates of the minutia location, $(x', y')$, and orientation, $\theta$, are obtained by finding:

$$\min_{x',y',\theta} D(x', y') = \int\int \left(I(x, y) - m(\bar{x}, \bar{y})\right)^2 dxdy,$$
$$\text{with } \begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x - x' \\ y - y' \end{pmatrix}.$$

Starting with a location estimated by any existing minutia-detection algorithm, and correcting for known biases, the minutia can be located more accurately by optimizing the function given above. Here we have used gradient descent (about five iterations suffice) to improve the translation and rotation parameters of the minutia.

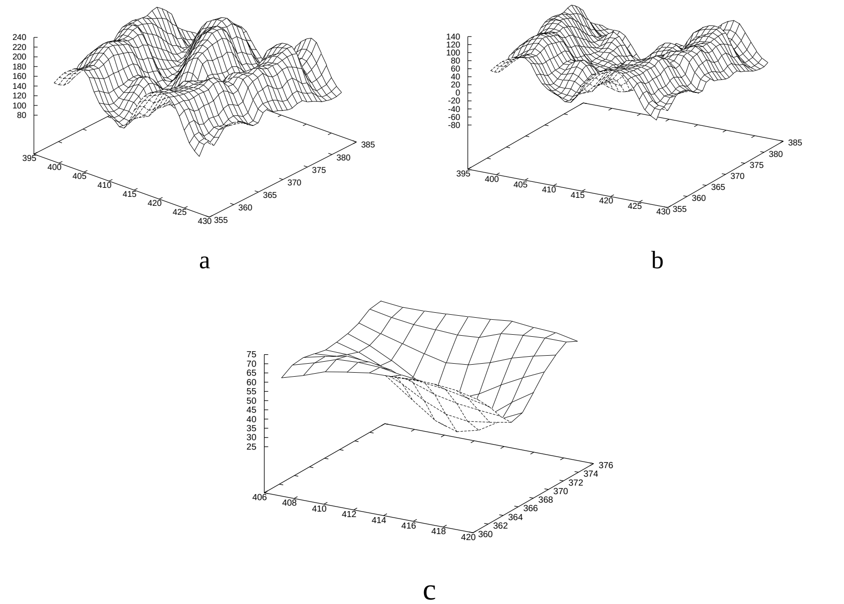


**Fig. 7** Fitting the ideal minutia. (a) The original minutia, (b) the surface with the fitted minutia subtracted, (c) the error surface $\sqrt{D(x', y')}$ for fixed $\theta$.

Fig. 7 shows a small section of a fingerprint image with grey values plotted as heights. (The dark ridge pixels are show with high values). A minutia is shown centered in the plot. Below, we show the mean-squared distance between the minutia model and the actual minutia for points in the neighbourhood of the minutia (fixed angle). A distinct local minimum marks the position of the true minutia as defined by our constructive definition. In Fig. 7b we have subtracted out the matched model to show that the minutia is well fit by the model. The minutia is located at the standardized minutia location, with sub-pixel accuracy, and increased angular resolution. By using the standard minutia definition, a fingerprint encoded using these locations can be accurately compared to a fingerprint encoded to the same standard by any other feature extraction software from any vendor.

## 5 Conclusions

We have developed a definition of an image function of a minutia (ridge ending – a ridge bifurcation can be defined on the inverse image, as a valley ending). This image function can be fitted to image data of a minutia and give a sub-pixel position of the minutia point.

The definition allows for establishing the ground truth of minutiae for fingerprint images. The minutiae can be annotated consistently by fingerprint experts. The definition provides a means for comparing minutia extraction algorithms from different vendors and vendors can compensate for biases in their algorithms.

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