all fingers of a criminal subject and collected millions of fingerprints. Today, the FBI's database comprises more than 227 million cards[21] [Scigliano1999], which makes positive identification a difficult task. Great strides have been made to build Automated Fingerprint Identification Systems (AFIS) in the past 15 years. Now the work culminates in the *IAFIS*[22]-project, which holds the promise of soon allowing the identification of latent prints and live scans with any digitally recorded ten-print card.

With the advent of passports, some countries traditionally required the bearer to record his thumbprint on the passport. Welfare as well as border and immigration control were the next applications that started using fingerprint recognition as a means of identification.

In the last two decades, many live fingerprint scanners and automated verification systems have been developed. Now that we have affordable sensors, a good understanding of the technology and enough reliable systems at our disposal, civil applications become accessible to biometrics [Newh2000, Jain2000a]. Fingerprint verification has already become popular in some areas such as access control, financial security and verification of firearm purchasers and driver's license applicants [FBI1984, Lee1991]. In other applications, such as ATM card verification, first pilot systems have been installed to test its performance and acceptance. The wide use of fingerprint verification in open applications seems to be quite imminent and reveals new challenging tasks, like performing the matching process in security tokens carried out in this thesis.

5.2 Basics of Fingerprint Analysis

This section explains the basic technical terms of fingerprint recognition[23]. For a detailed study of manual fingerprint examination, literature is presented in the references [Ashb1991, FBI1984, Safe1998, Olse1978, Ashb2000, Cowg1992, Durh1991].

Pattern Area:
The *pattern area* is defined as the main part of a fingerprint surrounded by the type lines. It is shown in figure 5.2.

Type Lines:
The two ridges, which start parallel on one side of the fingerprint and then diverge are the *type lines*. They define the pattern area and may not be continuous. If a break in the type line ridge occurs, the nearest ridge lying outside is considered a continuation.

[21] That means, the number of fingerprints the FBI has, totals 2.27 billion.

[22] IAFIS stands for Integrated AFIS.

[23] The examination of fingerprints employed as a method of personal identification is also referred to as *dactyloscopy*.

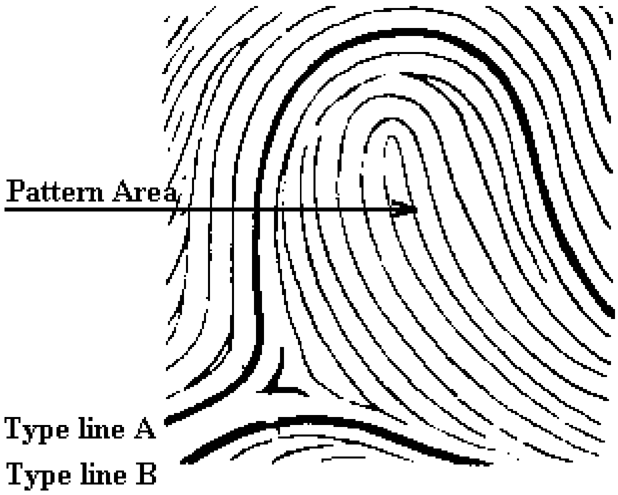

Figure 5.2: Type lines and the pattern area, from [FBI1984]

Core Point:
The *core point* is a singular point in the fingerprint, where the curvature of the ridges reaches a maximum. For simplicity, the core can be considered as a U-turn or the ridge ending enclosed by it in the fingerprint. It serves as an approximation to the center of a fingerprint image. Core points are pictured in figure 5.3.

Delta Point:
Another important kind of singularity in a fingerprint image is the so-called *delta point*. A delta is a place where two lines run side-by-side and then diverge with a significant pattern area in front of the divergence. In layman's terms it means that a triangle is formed. To find the right delta, the nearest ridge point to the center of divergence of type lines is taken. It may be a *ridge end* or a *ridge bifurcation* (see section 5.4). If there is more than one point opening toward the core at the point of divergence of two type lines, the nearest one to the core is selected as delta point. Figure 5.3 shows two different kinds of delta points.

Automated singular point detection is addressed in chapter 6.9. For a comprehensive study of singular points, the reader is referred to [FBI1984, Sher1993, Hong1999a, Rao1978, Rao1990, Karu1995, Hung1996, Jian1991, Srin1992].

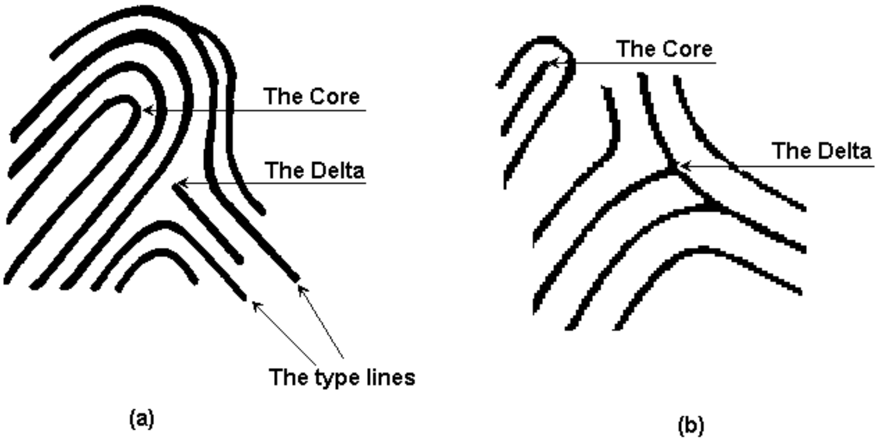

Figure 5.3: Core and delta point, from [FBI1984]

5.3 Fingerprint Classification

One of the basic tasks in fingerprint analysis is the *classification*. Every fingerprint is assigned a predefined class according to its global pattern configuration. The *Henry* system divides fingerprints into four main groups which are arches, loops, whorls and compounds and is the basis for other classification systems [Henry1904, Bridges 1942, Cherrill 1954]. The FBI classification system uses three main classes which are arches, loops and whorls. These are subdivided into plain arch, tented arch, radial loop, ulnar loop, plain whorl, central pocket loop, double loop and accidental whorl [FBI1984]. The number of distinguished pattern configurations is expressed by calling it the *five-class* or *ten-class* problem, for example.

5.3.1 Arch patterns

An *arch* is a fingerprint pattern of convex lines flowing from one side to the other without significant singularities. Arches make up about 5% of the total fingerprints and come in two flavors [Safer1998]:

- **Plain Arch**
  A *Plain Arch* pattern consists only of ridges that flow “easily” with only a slight wave form over the image. It does not contain any delta and no significant core. Figure 5.4 shows a plain arch on the left hand side.

- **Tented Arch**
  A *Tented Arch* has a similar global configuration, but the ridges in the center do not enter on one side of the impression and flow out upon the other side. There are three kinds of tented arches[24]:

[24] It should be noted, that according to the technical specification, arches need not to have deltas. A manual fingerprint examiner would not accept the lookalike point in Figure 5.4 for example as a true delta, because either the significant pattern area or the divergence is missing. In automated classification systems, where one

1. The type, in which ridges in the center form a definite angle.
2. The type with a significant upthrust in the center.
3. The type approaching the loop type described below lacking one of its essential characteristics. A fingerprint with a delta but without a sufficient recurve is considered a tented arch, for example.

Figure 5.4 shows a tented arch on the right hand side.

Figure 5.4: Plain arch and tented arch

5.3.2 Loop patterns

The ridges in a *loop* pattern arrange themselves in the form of a lasso, making a backward turn without a twist. At least one ridge enters on one side, curves and exits on the same side. It must have one –and only one– delta and one core. With proper aligning, the position of the delta point is lower than the core point. Loops are the most common pattern type found and make up about 60 to 65% of the total fingerprints [Safe1998]. If the delta is on the right hand side and the ridges about the core have a downward trend towards the left, it is known as a *left loop* (see Figure 5.5, left hand side). If the delta is on the left side and the center ridges tilt towards the right, it is known as a *right loop* (see Figure 5.5, right hand side).

The original classification of loop patterns is subdivided into *ulnar* and *radial loops*. If a loop opens up to the little finger, it is classified as an ulnar loop and if it opens up to the thumb-side, it becomes a radial loop. If a left loop or right loop is an ulnar or radial loop, depends on whether it was taken from the left or right hand.

needs to estimate delta points with Poincaré indices or something comparable, the distinction between true and false deltas is impossible. For simplicity, a tented arch is sometimes considered to must have a delta [Jain1998a, Hong1999a], which represents only the third type of tented arch. The detailed manual classification procedure with many examples is found in [FBI1984].

 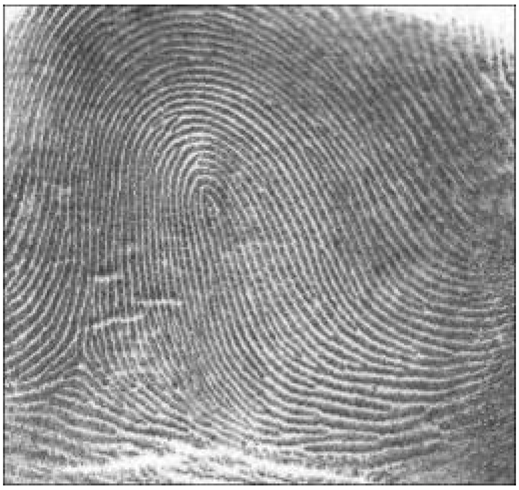

Figure 5.5: Left loop and right loop

5.3.3 Whorl patterns

When the ridges form a revolution around the center, the fingerprint is called a *whorl*. A whorl has at least two deltas and global convex ridges. At least one ridge makes a complete circle, giving an overall circular effect within the pattern area. The whorl pattern type constitutes about 30 to 35% of all fingerprints [Safe1998]. A whorl can be further divided into four subclasses which are plain whorl, central pocket loop, double loop and accidental. Figure 5.6 shows examples of whorl fingerprint types.

- **Plain whorl**
  A *plain whorl* has two deltas and at least one ridge which makes a complete circle. If an imaginary line is drawn between two deltas, the line must touch at least one of the recurving ridges within the pattern area. (see Figure 5.6a)

- **Central pocket loop**
  A *central pocket loop* has two deltas and at least one ridge makes a complete circle. If an imaginary line is drawn between two deltas, the line must not touch any recurving ridges within the pattern area. (see Figure 5.6b)

- **Double loop**
  A *double loop* whorl consists of two separate and distinct loop formations with two separate and distinct shoulders and two deltas. (see Figure 5.6c)

- **Accidental whorl**
  An *accidental whorl* is a comparatively uncommon pattern, being a complication of the whorl type. It is a pattern that consists of two different types of patterns. The accidental whorl has more than two deltas and is often referred to as *composite*. (see Figure 5.6d)

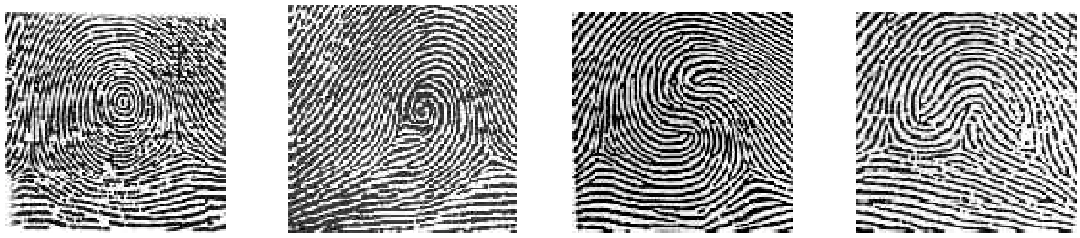

Figure 5.6: Whorl patterns (left to right): plain, central pocket, double loop, composite

Automated fingerprint classification has been addressed by many scientists [Capp1999a, Capp1999b, Capp2000c, FBI1984, Hong1999a, Jain1998a, Jain1999c, Jain1999d, Kami1992, Karu1996, Luk1991, Lumi1997, Lumi1999, Maio1996, Prab2000, Prin1985, Rao1980]. A correct classification is not sufficient for verification purposes, because many individuals will have the same configuration. It is useful for AFIS systems, where one needs to cut down the number of comparisons made. If a fingerprint is classified as a left loop, it needs not to be compared against any print filed as whorl, thus saving computing time. In most automated fingerprint classification efforts, directional images are used to find the core and delta points. The position and relation of these points are sufficient to solve the classification into the base classes or the following six: arch, tented arch, left loop, right loop, whorl, accidental/scar [Karu1996].

5.4 Minutiae Fingerprint Features

Sir Francis Galton first defined the features of a fingerprint [Galton1892]. Certain local point patterns called *minutiae* or *Galton details* are the most important marks for identification purposes. They were first characterized into the following:

- **Ridge Ending**
  A *ridge ending* is where a ridge begins or ends abruptly. A ridge may be quite long or very short. It needs to be followed to its end point to find a ridge ending. (see Figure 5.7a)

- **Bifurcation**
  A *bifurcation* is where a ridge is divided or forked into two or more parallel ridges. (see Figure 5.7b)

- **Divergence**
  A *divergence* is the spreading apart of two ridges which run parallel to each other. (see Figure 5.7b)

- **Lake**
  A *lake* is the joining of two bifurcations where one forms the left side and the other one forms the right side. Alternatively it could be described as a ridge bifurcating and making a small circular or an elliptical shape and then rejoining that ridge. (see Figure 5.7c)

- **Independent Ridge**
  An *independent ridge* resembles a ridge ending but this is a small ridge which is separated from the ridge on both sides. (see Figure 5.7d)

- **Spur**
  A *spur* is a combination of an independent ridge and a bifurcation. One of the bifurcation's lines is smaller than the other. (see Figure 5.7e)

- **Crossover**
  A *crossover* appears as an independent ridge which crosses over a space between two parallel ridges. (see Figure 5.7f)

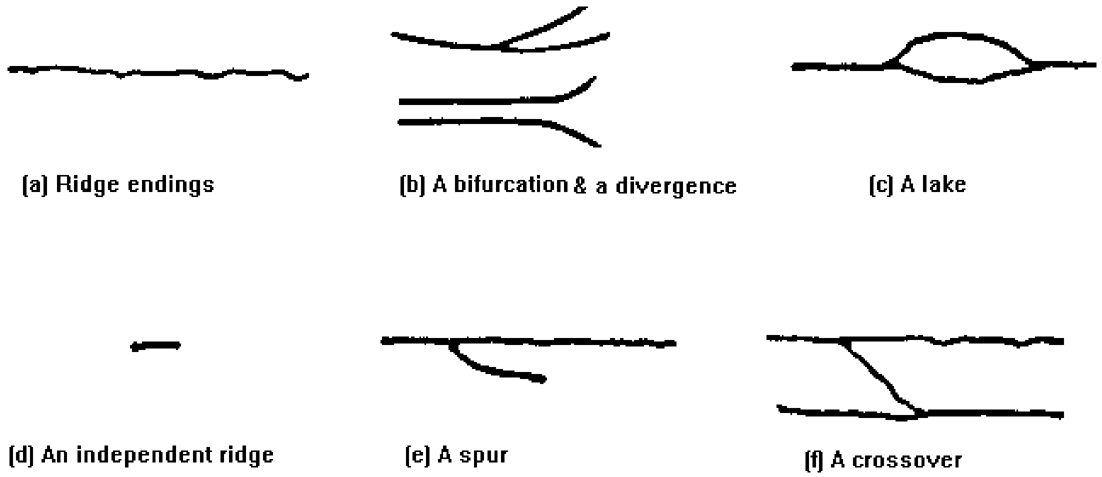

Figure 5.7: Galton details

Manual fingerprint verification uses an enlarged list of detailed structures with as much as 18 different features including *trifurcation*, *dot*, *eye* and *island*. A total of 150 local ridge characteristics have been identified [Moen1971]. Most of the automated fingerprint recognition systems rely on ridge endings and bifurcations only and measure their position and *orientation* (see below). Other features are neglected or considered as a combination of these basic types. The relative positions between neighboring minutiae, in particular the distance and relative angle are used for manual and automated fingerprint verification. Details on automated minutia matching will be given in section 7.1.

The orientation of a basic feature represents the direction of the ridge it resides on. It is measured as the angle formed by the tangent to the ridge and the horizontal axis. The orientation of a ridge end and a bifurcation is depicted in the following figure (5.8).

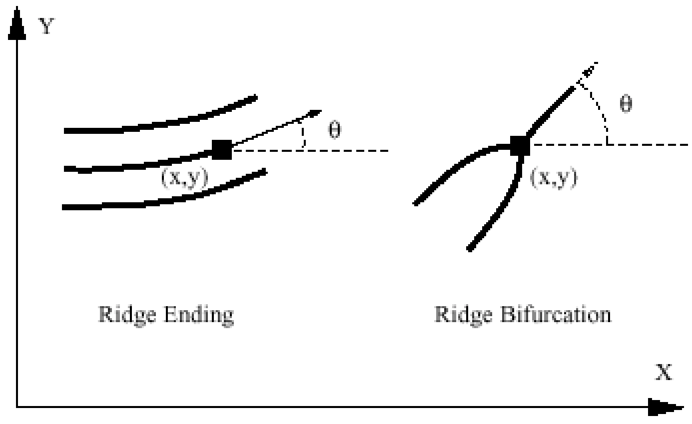

Figure 5.8: Features for automated fingerprint verification, from [Hong1998b]

5.5 Ridge Counts

The FBI classification does not stop when the five-class or ten-class problem is solved. Instead, a line is drawn between the core and delta points and the number of intersecting ridge lines counted. The result is called *ridge count* and gives a more specific classification noted on any ten-print card [FBI1984]. More specifically, any ridge or feature touched or crossed by the imaginary line from the core to the delta is counted as a ridge. The following figure (5.9) from [FBI1984] shows three fingerprints with different ridge counts:

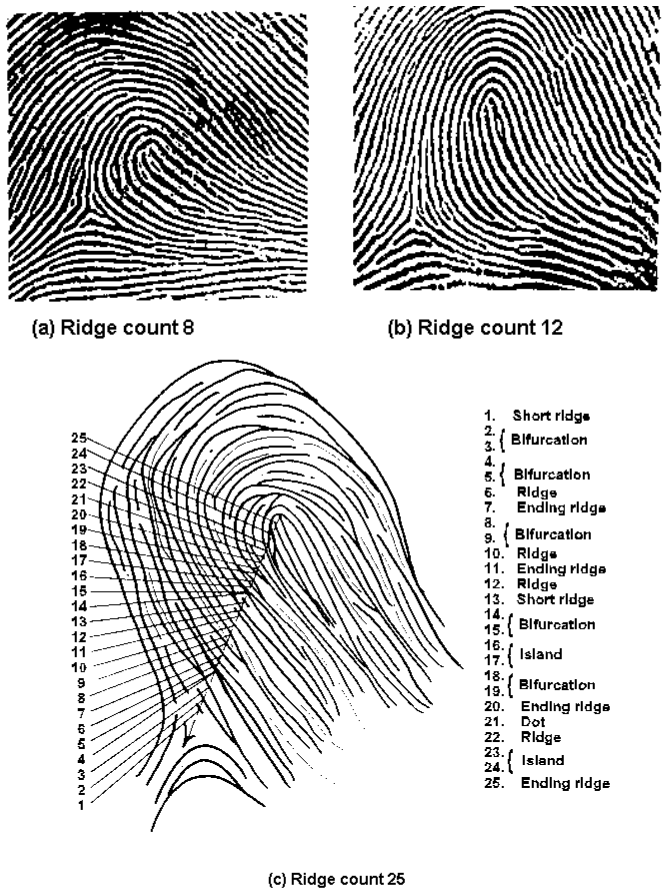

Figure 5.9: Ridge counts, from [FBI1984]

Ridge counts provide valuable information not only for classification but also for matching purposes. They can similarly be used for the features as for the singular points. In addition to the minutia position and orientation, the relative distance and angle are enhanced by the ridge count between neighboring minutiae. The following figure (5.10) shows a sample fingerprint with some exemplifying ridge ends, bifurcations and ridge counts between them.

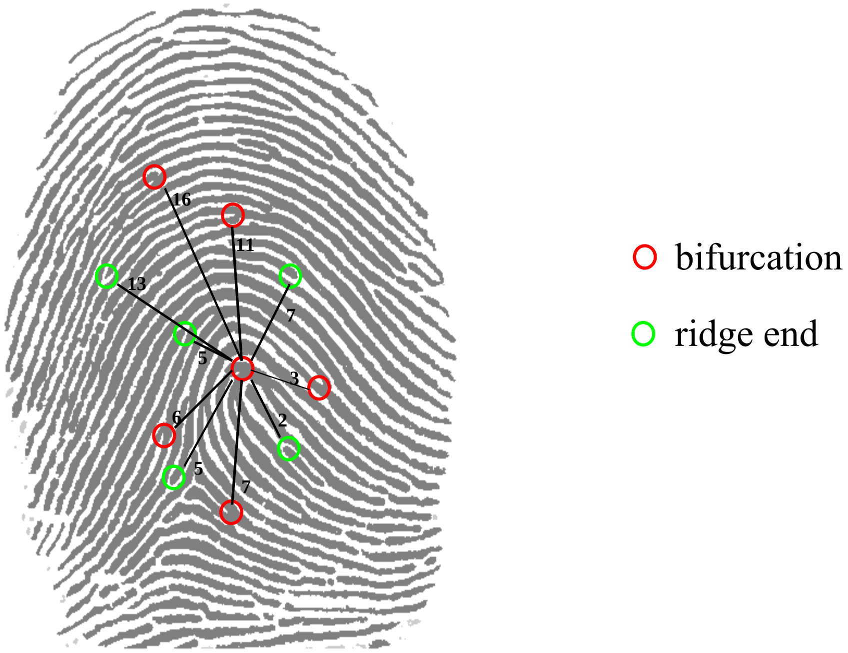

Figure 5.10: Minutia ridge count samples

Manual fingerprint examiners and forensic scientists always take the ridge counts between minutia as a superior measure to positively identify fingerprints. This technique is also known as *coincident sequencing* and is recognized by law enforcement agencies worldwide. The use of ridge counts in automated fingerprint verification systems started with the publications [Guna1991a, Guna1991b, Cost1994]. The main advantage of ridge counts is their independence from the distance of two minutiae. Due to skin elasticity and also optical distortion of sensing devices, the distance of two detected minutiae will sometimes show considerable variations. With measuring ridge counts instead of distances, one could even enroll an individual as a child and verify him or her as an adult. The use of ridge counts in computerized systems is patented by B. Costello [EP1987], co-founder of the U.S. company Printscan International Inc.[25].

5.6 Poroscopy

The uniqueness and permanence of sweat pores was observed as early as 1912 by Locard [Loca1912]. Even as the positions and shapes of pores play an important role in manual fingerprint verification and forensic sciences [Ashb1982, Ashb1991, Czar1995, Kuhn1994], it is somewhat surprising that only a few researchers have ever made the effort of automated evaluation of this useful information found in fingerprints [Stos1994, Rodd1999]. In fact, fingerprint verification can be subdivided into *edgeoscopy*, the verification of minutiae, and

[25] In spite of that fact, the majority of AFIS vendors and at least a significant portion of firms offering fingerprint verification seem to use the ridge counts without contributions.

poroscopy, the verification of sweat pores [Ashb2000][26]. The reason for not using pores in commercial systems may be the need for high resolution scanners. FBI and NIST propose a resolution of 500 dpi for live fingerprint scanners [NIST1999]. This seems to be sufficient, as the size of ridges ranges from 200 to 300 µm. The smallest pores measure only 60 µm, so that a scanner should have at least 800 dpi for poroscopy, assuming a double sampling rate [Stos1994]. The position, size and shape of pores are unique characteristic features, that could enhance minutia-based verification. A fingerprint image with clearly visible pores is depicted in Figure 5.11. On the right hand side, the pore positions extracted with an algorithm described in chapter 7.3 are superimposed on the original image.

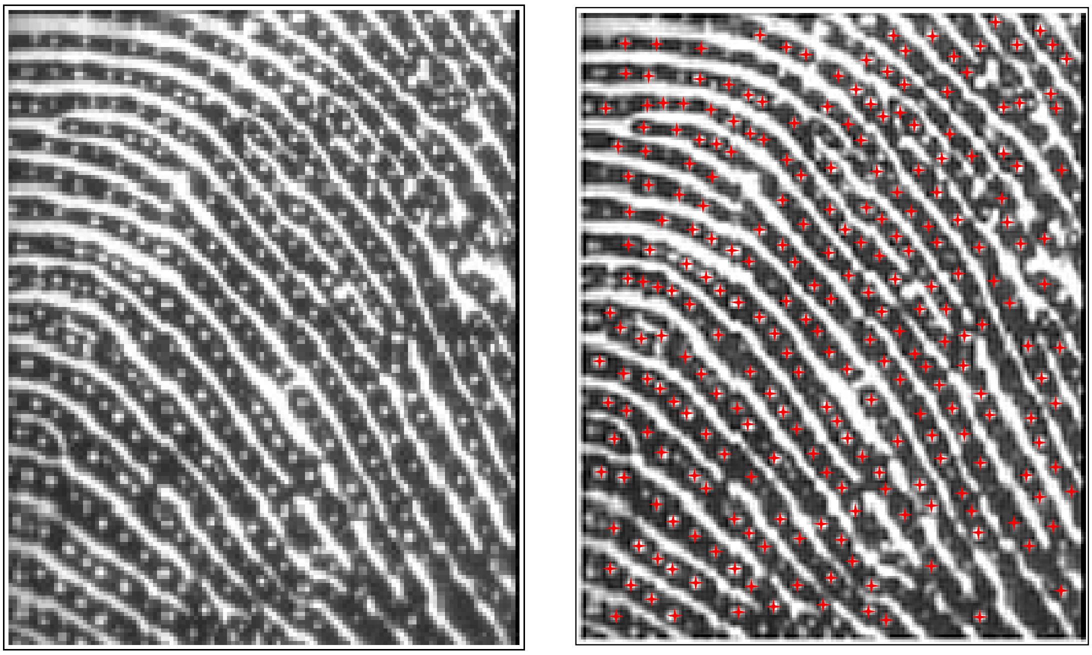

Figure 5.11: Fingerprint fragment with pores, raw image from [Stos1994]

A fingerprint may contain up to 2700 pores [Ashb1982, Czar1995]. Their size, shape and location can be used as features for fingerprint comparison. In contrast to bifurcations and ridge ends, pores do not have a direction. The automated matching of pores will be explained in chapter 7.4.

The minimal resolution of 500 dpi as specified by NIST and FBI's IAFIS certification has lead to a nearly de-facto standard. The majority of live sensors supports this resolution. Only a few manufacturers offer suitable sensing devices with higher resolutions as required for reliable pore detection. Poroscopy has the potential to enhance minutia-based fingerprint verification, as will be shown and empirically proven within this thesis.

[26] The current art and practice of manual fingerprint verification is also referred to as *ridgeology*, that encompasses not only minutiae and pore evaluation, but represents a concept of understanding and explaining the process carried out by a fingerprint examiner.

5.7 Sensor Technologies

In forensic sciences, latent fingerprints used to be lifted with the aid of powder and tape and a subject's fingerprints collected with inked impressions [FBI1984]. For civil applications, in particular verification systems, a live sensor is needed to acquire fingerprint images. This section briefly describes the different available sensing technologies.

5.7.1 Optical fingerprint sensors

This category is the oldest and most mature technology. A finger is placed against a glass platen, which represents the edge of a prism. The prism is illuminated on one side, while the reflected light is imaged by a CCD[27] or CMOS[28] camera on the other side. Reflection of light is suppressed, where the skin contacts the surface, that means where the fingerprint's ridges touch it. Therefore, this method is also referred to as frustrated *total internal reflection* (TIR). Figure 5.12 pictures the sensing procedure. Another common method is using a beamsplitter as shown in figure 5.13.

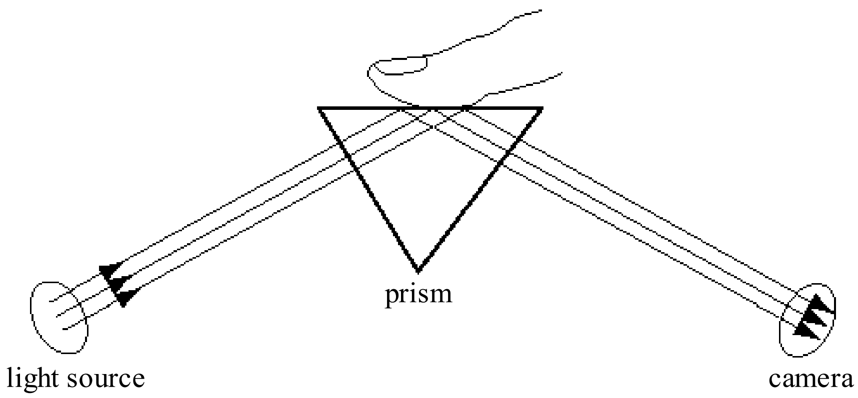

Figure 5.12: Optical imaging with frustrated TIR

[27] CCD = Charge Coupled Device

[28] CMOS = Complementary Metal Oxide Semiconductor

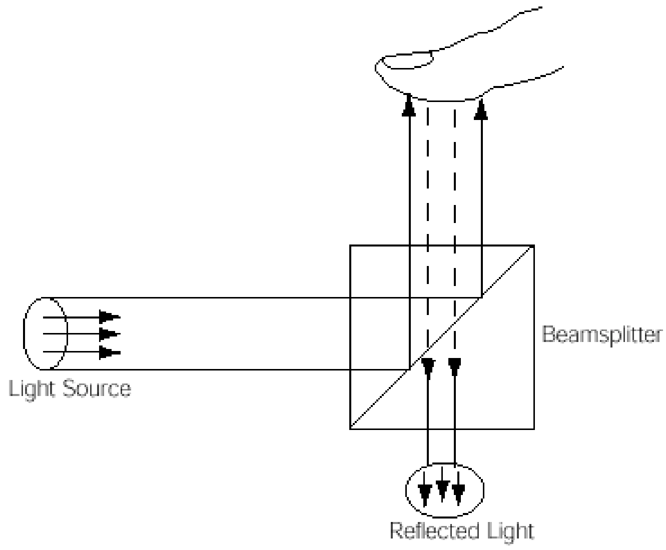

Figure 5.13: Optical imaging with beamsplitter, from [Drak1996]

Optical fingerprint sensors generally provide excellent image quality. Although, there are great differences between low-cost variants and reference models. The resolution ranges from 256 dpi up to 1000 dpi according to manufacturer's specifications. The active sensing surface varies from 0.5×0.5 square inches to more than 1.0×1.0 square inches for rolled fingerprints. Some sensors carry a soft coating on the glass prism to enhance the contrast of particularly dry fingers. The silicone coating tends to wear off quickly and limits the application space. Manufacturers include such companies as American Biometric Company, CrossMatch Technologies, Digital Persona, Identicator (with Compaq), Identix, Fujitsu, Mitsubishi, Polaroid, SAC Technologies, SecuGen and Sony. Some of these devices have a built-in live-and-well-test, that recognizes fake and artificial fingers.

5.7.2 Ultrasonic sensor

Another type with brilliant image quality is the ultrasonic sensor manufactured solely by UltraScan. It uses ultrasound instead of light that is reflected by the finger sensed. This sensor is not affected by dirt, grease or dry fingers and is preferable for verifying infants due to its high resolution of 1000 dpi.

5.7.3 Capacitive sensor chips

The use of optical scanners is limited to desktop sized devices. Due to the optical path length required, even the smallest optical sensor has half the size of a PC mouse. Some chip manufacturers have independently designed a solid-state silicon fingerprint sensor. It is a chip configured as an array of capacitor plates. The contacting skin acts as the opposite plate of a capacitor. The capacity for every cell is measured via the conductance and corresponds to the skin distance. A digital image is generated from the different capacities measured and transmitted to the host system.

Sensors of this category can easily be integrated into small embedded systems like mobile phones and may one day also fit into an ISO smart card. The manufacturers are going to keep their promise of low target prices, as soon as mass production has been realized. This technology is offered in products by Infineon, Pollex, Sony, ST Microelectronics and Veridicom with quite similar specifications. In spite of wearing sophisticated coatings, any capacitive chip can suffer from electrostatic discharge (ESD) and mechanic stress.

5.7.4 Electrical field sensor chips

The Authentec company developed a chip similar to the capacity sensing chip with the exception that it does not sense the conductance, but the electrical field between skin and silicon. It operates by generating an electric pulse around the perimeter of the IC and measuring the electrical field at each location of an array of receiving elements. The device is claimed to be superior both in terms of image quality and durability. The *e-field sensor*, however, may be more susceptible to damage caused by ESD.

5.7.5 Direct optical chips

Direct optical chips try to combine the brilliant optical image quality with the advantages of chip technology, namely easy hardware integration and low prices. The Ethentica[29] company developed a polymer-based sensor, that illuminates with an internal layer and transforms the fingerprint into a digital image. The chip is made by Philips.

A completely different approach is taken by the German Delsy company. This manufacturer uses infrared throughput light on a CCD- or CMOS-chip to acquire images. With a durable fiber-optics surface, this sensor is gas and water tight and therefore deployable even in a rugged environment. Additionally, it carries an excellent live and well test by measuring an individual’s pulse and the oxygen concentration in the circulating blood.

5.7.6 Line sensor chips

The cheapest production costs can be achieved, when the sensor is not a whole chip, but only a linear array as in many flatbed scanner devices. The finger to be sensed is *swiped* over the array and produces a fingerprint image, that is 10 to 20 times the sensor size. Thomson CSF[30] was the first company to implement this idea in a fingerprint sensor chip. It measures temperature differences of the skin and transforms them into digital images, that are assembled to a total fingerprint in software. Some practice with the feedback of a live image is required to create acceptable fingerprint images.

Another line-sensor is offered by Kinetic Sciences Inc.. This device uses a linear optical array to produce images from a finger, that is moved over. The optical image quality is better than the images generated with thermal sensing, but sometimes, the currently offered software fails to paste the partial images properly.

[29] formerly Who?Vision

[30] now Atmel Grenoble

Line sensors target very small and low-priced end products, since the final price of a semiconductor circuit is, as a rule of thumb, proportional to the surface area of the chip.