FINGERPRINT IMAGE ENHANCEMENT, SEGMENTATION AND MINUTIAE DETECTION

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Blekinge Institute of Technology
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Abstract

Prior to 1960's, the fingerprint analysis was carried out manually by human experts and for forensic purposes only. Automated fingerprint identification systems (AFIS) have been developed during the last 50 years. The success of AFIS resulted in that its use expanded beyond forensic applications and became common also in civilian applications. Mobile phones and computers equipped with fingerprint sensing devices for fingerprint-based user identification are common today.

Despite the intense development efforts, a major problem in automatic fingerprint identification is to acquire reliable matching features from fingerprint images with poor quality. Images where the fingerprint pattern is heavily degraded usually inhibit the performance of an AFIS system. The performance of AFIS systems is also reduced when matching fingerprints of individuals with large age variations.

This doctoral thesis presents contributions within the field of fingerprint image enhancement, segmentation and minutiae detection. The reliability of the extracted fingerprint features is highly dependent on the quality of the obtained fingerprints. Unfortunately, it is not always possible to have access to high quality fingerprints. Therefore, prior to the feature extraction, an enhancement of the quality of fingerprints and a segmentation are performed. The segmentation separates the fingerprint pattern from the background and thus limits possible sources of error due to, for instance, feature outliers. Most enhancement and segmentation techniques are data-driven and therefore based on certain features extracted from the low quality fingerprints at hand. Hence, different types of processing, such as directional filtering, are employed for the enhancement. This thesis contributes by proposing new research both for improving fingerprint matching and for the required pre-processing that improves the extraction of features to be used in fingerprint matching systems.

In particular, the majority of enhancement and segmentation methods proposed herein are adaptive to the characteristics of each fingerprint image. Thus, the methods are insensitive towards sensor and fingerprint variability. Furthermore, introduction of the higher order statistics (kurtosis) for fingerprint segmentation is presented. Segmentation of the fingerprint image reduces the computational load by excluding background regions of the fingerprint image from being further processed. Also using a neural network to obtain a more robust minutiae detector with a patch rejection mechanism for speeding up the minutiae detection is presented in this thesis.

Keywords: adaptive fingerprint image enhancement, fingerprint segmentation, gray-scale image normalization, minutiae features, neural networks, frequency analysis, kurtosis.

To my daughter Freja, may you have a bright future!

Acknowledgments

Firstly, I wish to thank my supervisor, Prof. Ingvar Claesson for giving me the opportunity to conduct the research I love, and for providing me with the freedom and independence that have been essential to the making of this thesis. My sincere thanks to my two co-supervisors over the years; Dr. Mikael Nilsson who got me started in my studies, and Dr. Benny Sällberg, who helped me to conclude them. Your feedback and constructive criticism have been a great asset to me.

I would also like to thank former and present colleagues at the Department of Applied Signal Processing. The casual conversations at lunch, technical discussions and parties have all contributed to a great environment at the department. Especially I would like to thank my dear friend Dr. Mikael Swartling for joining me on the journey to study the field of signal processing making the relocation much more enjoyable; Dr. Thomas Sjögren for being a really good friend who supported me in times when I really needed it; Dr. Muhammad Shahid my former office mate and a good friend with whom I had endless discussions and idea exchanges on topics reaching far outside our research areas; Kristian Nilsson for being very helpful at the department and for being a great host/guide on Öland; and finally Irina Gertsovich with whom I closely work at the department and thus able to discuss ideas within shared field of research.

A special thank you also goes to my family for all the support I have received throughout the years.

Josef Ström Bartůněk
Karlskrona, December 23, 2015

Preface

This doctoral thesis presents my research work in the fields of fingerprint image enhancement, segmentation and minutiae detection, which I performed at the Department of Applied Signal Processing at Blekinge Institute of Technology, Sweden. The thesis is composed of six parts that present the following research contributions:

Part I J.S. Bartůněk, M. Nilsson, J. Nordberg, and I. Claesson, "Adaptive fingerprint binarization by frequency domain analysis", in *Fortieth Asilomar IEEE Conference on Signals, Systems and Computers*, pp. 598-602, 2006.

Part II J.S. Bartůněk, M. Nilsson, J. Nordberg, and I. Claesson, "Improved adaptive fingerprint binarization", in *IEEE Congress on Image and Signal Processing*, pp. 756-760, 2008.

Part III J.S. Bartůněk, M. Nilsson, B. Sällberg, and I. Claesson, "Adaptive fingerprint image enhancement with emphasis on preprocessing of data", in *IEEE Transactions on Image Processing*, 22(2):644-656, 2013.

Part IV J.S. Bartůněk, B. Sällberg, M. Nilsson, and I. Claesson, "Adaptive Normalization and Segmentation of Fingerprint Images based on Kurtosis Statistics", submitted to *IEEE Transactions on Information Forensics and Security* in 2015.

Part V J.S. Bartůněk, M. Nilsson, J. Nordberg, and I. Claesson, "Neural network based minutiae extraction from skeletonized fingerprints", in *IEEE Region 10 Conference TENCON*, pp. 1-4, 2006.

Part VI J.S. Bartůněk, B. Sällberg, M. Nilsson, and I. Claesson, "Optimization of a fingerprint minutia detector using statistical pattern analysis", submitted to *IEEE Letters Signal Processing* in 2015.

During my PhD studies, I have also been involved in production of the following research work that is not an integral part of this thesis.

- I. Gertsovich, J.S. Bartůněk, L. Håkansson, and M. Nilsson, "A novel methodology for the interoperability evaluation of an iris segmentation algorithm", in *Sixth IEEE International Conference on Biometrics: Theory Applications and Systems (BTAS)*, pp. 1-6, 2013.

- I. Gertsovich, J.S. Bartůněk, L. Håkansson, and M. Nilsson, "Shoeprint image recognition methods: literature review and possible developments", in *Conference on SSBA*, 2013.

- M. Swartling, J.S. Bartůněk, K. Nilsson, I. Gustavsson, and M. Fiedler, "Simulations of the VISIR open lab platform", in *9th International Conference on Remote Engineering and Virtual Instrumentation (REV)*, pp. 1-5, 2012.

- I. Gustavsson, L. Claesson, K. Nilsson, J. Zackrisson, J. Garcia Zubia, U. Hernandez Jayo, L. Håkansson, J.S. Bartůněk, T. Lagö, and I. Claesson, "The VISIR Open Lab Platform, Book chapter in Internet Accessible Remote Laboratories: Scalable E-Learning Tools for Engineering and Science Disciplines", in *Chapter 15: The VISIR Open Lab Platform. IGI Global, 1 edition*, ISBN 1613501862, 2011.

- M. Nilsson, I. Gertsovich, and J.S. Bartůněk, "Mouth open or closed decision for frontal face images with given eye locations", in *Fourth IEEE International Conference on Biometrics: Theory Applications and Systems (BTAS)*, pp. 1-6, 2010.

- S. Maddala, J.S. Bartůněk, and M. Nilsson, "Implementation and evaluation of nist biometric image software for fingerprint recognition", in *International Conference on Signal and Image Processing (ICSIP)*, pp. 207-211, 2010.

- M. Nilsson, J.S. Bartůněk, J. Nordberg, and I. Claesson, "On histograms and spatiograms - introduction of the mapogram", in *15th IEEE International Conference on Image Processing (CISP)*, pp. 973-976, 2008.

- M. Nilsson, J.S. Bartůněk, J. Nordberg, and I. Claesson, "Human whistle detection and frequency estimation", in *Congress on Image and Signal Processing*, pp. 737-741, 2008.
- I. Gustavsson, J. Zackrisson, J.S. Bartůněk, K. Nilsson, L. Håkansson, I. Claesson, and T. Lagö, "Telemanipulator for remote wiring of electrical circuits", in *Proceedings of the REV Conference*, 2008.
- I. Gustavsson, J. Zackrisson, J.S. Bartůněk, H. Åkesson, L. Håkansson, and T. Lagö, "An instructional electronics laboratory opened for remote operation and control", in *Proceedings of the ICEE Conference*, 2006.

Contents

Introduction

Until the 1960's, fingerprint matching was used solely for forensic purposes where human experts performed the fingerprint analysis manually. In the last 50 years, a great amount of effort developing automated fingerprint identification systems (AFIS) has been made and with this the identification performance has steadily improved over time. The automation of the fingerprint recognition process has been so successful that its use expanded beyond forensic applications and became common also in civilian applications.

Fingerprints exhibit remarkable individuality and permanency over time, i.e., fingerprints usually retain their characteristics as the person ages. In law enforcement, fingerprints are used as identification markers with satisfying results over many years. Thus, fingerprints have been observed to offer a more secure and reliable person identification method than keys, passwords or id-cards can provide. With fingerprint readers becoming cheaper and a steady reduction in the cost-performance ratio of computer power, automatic fingerprint recognition systems today provide an efficient and inexpensive alternative to ordinary solutions in person identification. Mobile phones and computers equipped with fingerprint sensing devices for fingerprint-based password protection are being produced to replace ordinary password protection methods.

This introductory chapter is organized as follows: A motivation for the work is presented in section 1. The fingerprint pattern, its representation, how it is being sensed and fingerprint quality is described in section 2. Fingerprint recognition, a general system overview and its sub-modules, is described in section 3. An introduction on how the performance evaluation is usually conducted is provided in section 4. The research objectives and the scope of the thesis are given in section 5. The thesis outline with a summary of research contributions are presented in section 6. Finally, concluding remarks on the contributions made in this thesis and a discussion of future research possibilities are given in section 7.

The main research contributions of this thesis are presented in the six parts that follow this introduction. These parts are all based on individually published research papers.

1 Motivation

During its long history, fingerprint pattern analysis research has developed into a field with numerous sub-fields (see, e.g., [1] for a survey of AFIS methods). Among these fields, fingerprint matching is still growing due to several reasons. A major problem in automatic fingerprint identification is to acquire reliable matching features from fingerprint images with poor quality. Images where the fingerprint pattern is heavily degraded usually inhibit the performance of an AFIS system [2]. The performance of AFIS systems is also reduced when matching fingerprints of individuals with large age variations [3, 4]. The interoperability where matching is performed with the use of cross-sensors has also shown to be problematic [5]. The present activity in the research community and the broad variety of new publications indicate that there is a strong and continuing interest in this field [6].

This thesis presents contributions within the field of fingerprint image enhancement, segmentation and minutiae detection. The reliability of the extracted fingerprint features is highly dependent on the quality of the obtained fingerprints. Unfortunately, it is not always possible to have access to high quality fingerprints. Therefore, prior to the feature extraction, an enhancement of the quality of fingerprints and a segmentation are performed. The segmentation separates the fingerprint pattern from the background and thus limits possible sources of error due to, for instance, outliers. Most enhancement and segmentation techniques are data-driven and therefore based on certain features extracted from the low quality fingerprints at hand. Hence, different types of processing, such as directional filtering, are employed for the enhancement. This thesis contributes by describing new research both in fingerprint matching and in the required pre-processing for the extraction of features to be used in fingerprint matching systems.

2 The Fingerprint Pattern

The skin on human fingertips contains ridges and valleys which together form distinctive and individual patterns. These patterns are commonly referred to as fingerprints. Fingerprint patterns are fully developed already in the fetal stage during pregnancy and they usually keep their characteristics throughout the whole lifetime [7]. The pattern of a fingerprint is controlled both by genes and by the environment. The cells on fingertips grow in a micro environment (uterus). Thus, fingerprints differentiate even in identical twins, despite the fact that they have identical genes. Variations such as the fetus' position in the uterus, the flow of amniotic fluid and other factors make it virtually impossible for two fingerprints to be exactly identical. Due to these variations, fingerprints of identical twins will differ on a micro-detail level [8].

While the uniqueness of individual fingerprint patterns cannot be absolutely certified, several studies, and the long use of fingerprints as evidence in law enforcement, have observed that no two fingerprints appear to be identical. Fingerprints are therefore considered as unique for every individual. Injuries like cuts, burns and bruises can temporarily damage the quality of fingerprints. However, when the injuries are fully healed, the same fingerprint pattern will reappear. Thus, fingerprints have been concluded to be both unique and permanent [1].

2.1 Fingerprint representation

A captured fingerprint pattern consists of bright (valleys) and dark (ridges) lines. The characteristics and behavior of the line pattern can be categorized into three feature (detail) levels: The overall global ridge pattern (level 1), minutiae points (level 2) and the local shape of ridge edges and pores (level 3) [1]. An illustration of these categories is provided in Fig. 1.

The level 1 features include not only the overall ridge pattern but also delta points, patterns with three different ridge directions and core points, and patterns with the highest ridge curvature around a ridge ending. Each fingerprint usually have up to two core and delta points. This feature level is usually considered too general and not suitable for proper person identification/authentication procedures. It can, however, be used for fingerprint classification.

The level 2 features describe the type, position and direction of small details in the fingerprint ridge structure. Minutiae point patterns are highly individual and they differ even between identical twins. The two most common minutiae points are ridge endings (termination) and bifurcations. Level 2 features are employed in most fingerprint matching methods.

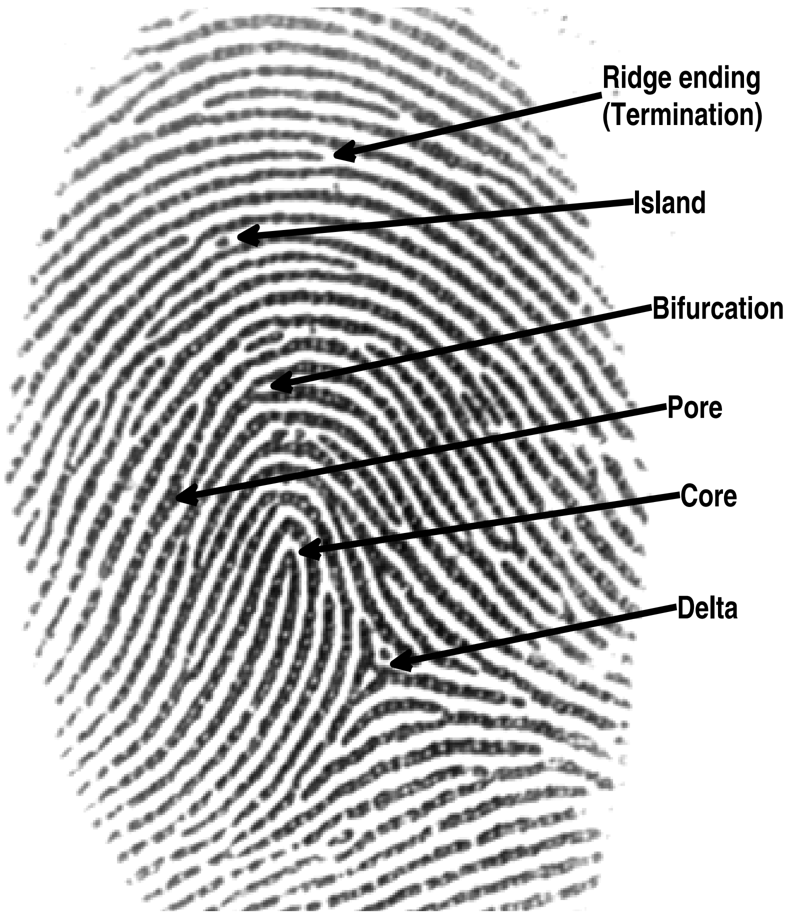


Figure 1: Typical plain fingerprint pattern with its features.

The level 3 features show highly individual characteristics. These features are used in applications requiring the greatest amount of detailed information. However, their level of detail is usually too fine granular for common fingerprint applications.

2.2 Fingerprint sensing

There are three main types of methods through which fingerprints can be obtained:

- Latent fingerprints that are lifted from flat surfaces.
- Fingerprints are obtained by applying ink directly on the fingertips which are then pressed/rolled (nail-to-nail) on a piece of paper. These are referred to as off-line inked impressions.
- An electronic fingerprint scanner is used to sample the fingertips, getting a direct, digital copy of the pattern. This is referred to as live scanning.

The latent and off-line inked impression methods are usually only used in forensic applications. The fingerprint samples need to be digitized by scanning or photographing them. Live-scan fingerprint scanners provide a large flexibility due to the varying functionality and wide range of scanner types available. Some scanners are designed for single-finger use, where only one finger at a time is acquired. Others have multi-finger capability where several fingers are acquired simultaneously. These scanners are often able to acquire plain/flat impressions where only a portion of the fingertip is captured. Scanners used in forensic applications mostly have the capability to capture rolled impressions where the entire fingerprint (nail-to-nail) is acquired. Sweep scanners capture several "slices" of the fingerprint. The final fingerprint image is then reconstructed by combining the captured slices.

Some type of optical or solid-state sensor is usually employed in fingerprint scanners. Optical sensors are cameras specially built for fingerprint pattern photography. The main components consist of a CCD/CMOS image sensor together with a glass/plastic prism and a light source. Optical sensors produce the highest fingerprint image quality. The high quality of those scanners come at the cost of a high price and these devices are usually bulky. The most common type of solid-state sensor uses capacitive sensing. The sensor consists of a two-dimensional array of micro-capacitor plates. Scanners with capacitive sensors are smaller and cheaper than scanners based on optical sensors, but are still able to produce images with sufficient quality for reliable fingerprint matching. Besides these examples of fingerprint sensors, there are numerous elaborate design variations of both optical and solid-state sensors. Since these variations of the standard sensors are uncommon, they have intentionally been omitted from this thesis.

2.3 Fingerprint image quality

The fingerprint image is a digital representation of the fingerprint pattern. The quality of the fingerprint image depends on many factors originating both from the condition of the fingertip skin and the characteristics of the method used to sample the finger. The user's interaction with the scanner (e.g., if a user presses strongly or loosely with his finger at the sensor) will also influence the overall fingerprint quality.

For fingerprint scanners there is an international standard, ISO/IEC 19794-4, that specifies the minimum requirements for the parameters of the captured fingerprint images. Fingerprint patterns are not dependent on skin color, thus only gray-scale levels are considered. The main parameters linked to image quality in this international standard are image resolution, pixel depth, dynamic range and a certification according to the standard. Image resolution is measured in pixels/centimeter (ppcm) or pixels/inch (ppi). Pixel depth is specified in the number of bits used to encode the gray-scale quantization levels. Dynamic range specifies the minimum number of gray levels that the image needs to have. The certification according to the standard guarantees the eligibility of the scanner for security applications.

The image quality is divided into four levels. Scanners designated to be used in security applications must have a minimum of 500ppi, 8bits and 220 gray levels. These scanners must also be certified. According to the standard, this is equivalent to the image quality level 2. In some applications, scanners require the image quality of level 1 which differs from level 2 by having a minimal image resolution of 1000 ppi. The standard also specifies the minimum requirements for the image quality of levels 3 and 4. However, scanners having a level below 2 generate fingerprint images with an insufficient level of detail and these are thus not suitable for fingerprint recognition in security applications.

Apart from using high-quality fingerprint scanners, the skin on the fingertip must be in a good condition. Some individuals, such as those engaged in heavy manual work or the elderly, lack prominent fingerprint patterns and will thus produce fingerprint images of low quality. Fingers that are either too moist or too dry or incorrectly placed on the scanner will also produce low-quality fingerprint images.

3 Fingerprint Recognition

Fingerprint recognition is a sub-class of biometric recognition where other anatomical (e.g., face and iris) or behavioral (e.g., speech and signature) characteristics beside fingerprints are considered. Fingerprint recognition is a general term for procedures where fingerprint patterns are analyzed in order to identify individuals. Depending on the application, the recognition can either be viewed as a verification or as an identification procedure. In verification applications, a fingerprint with a known identity (template) is compared to a fingerprint of an individual claiming to have that identity. Thus, only one-to-one comparison is required for the decision. In identification applications, the individual's fingerprint is matched against a database of fingerprints. Here, multiple comparisons (one-to-many) are needed to establish if the individual is in the database. Regardless of whether the purpose of the recognition procedure is verification or identification, recognition is based on a similarity measure between fingerprint pattern pairs. Thus, the same system can be employed for both the verification and the identification tasks since the same similarity measures are used for individual decision making.

3.1 System Overview

The system generating the similarity measure typically consists of multiple steps as described in Fig. 2. The main steps are the feature extraction and the feature matching. The features should be selected so as to capture the invariant representation of the fingerprint pattern. The matching procedure establishes corresponding features extracted from the fingerprint pattern pairs. These are then converted into similarity measures. Normally, one feature set is stored in a database as a template. Typically, a pre-processing step is performed on the raw fingerprint image in order to improve the feature extraction and thus improve the matching performance.

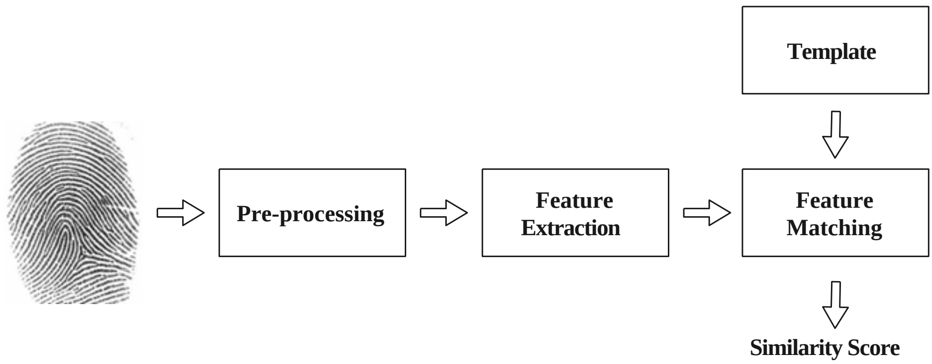


Figure 2: Scheme of the general fingerprint matching system.

3.2 Pre-processing

The pre-processing step often consists of a fingerprint image enhancement procedure. The pre-processing stage has shown to improve matching scores, especially for fingerprint images with low quality. Other procedures, such as segmentation, might also be performed in the pre-processing step to highlight the region of interest (the fingerprint pattern) in the image. Due to the relevance of fingerprint image enhancement to the work accounted for in this thesis, this process is described in detail in this sub-section.

Enhancement

The most popular fingerprint enhancement methods are based on contextual filtering. Contextual filtering means that topological filter features are aligned with the local orientation and frequency of the ridges in the fingerprint image. The method that first utilized contextual filters to enhance fingerprint images through the aid of both filter design and filtering in the spatial domain is presented in [9, 10]. This method used a main filter that had a horizontally directed pattern with a design based on four manually identified parameters for each fingerprint image. Additional directions were created by rotating the main horizontal filter while the filter size remained constant. Other fingerprint enhancement methods employ directional Gabor or Butterworth bandpass filters where the filtering is performed in the frequency domain [11, 12]. Second directional derivatives for filter design, and a method for selecting a suitable size of the local area, were presented in [13]. Estimation of the local fingerprint ridge features in the frequency domain was proposed by [14]. This approach enables a simultaneous estimation of both orientation and ridge frequency. A pyramid decomposition-based local feature estimation and filtering was proposed by [15]. Here, the fingerprint image is decomposed into subbands corresponding to different spatial scales. Then, a contextual smoothing is performed on those pyramid levels. A method based on curved Gabor filters that locally adapts the filter shape to the curvature and direction of the flow of the fingerprint ridges was introduced in [16]. This new type of Gabor filter design shows a potential advantage in fingerprint image enhancement in comparison to classical Gabor filter methods.

Another method that stands out from the classical directional filter design approaches was proposed in [17]. Instead of requiring tuned parameters for each fingerprint image, the magnitude spectrum of each local area of the fingerprint image was directly used to filter the same local area in the frequency domain. The rationale behind this method is that the local magnitude spectrum carries properties similar to a matched filter, and by using the magnitude spectrum directly as a filter, dominant components related to ridges are amplified. It should be noted that this approach also increases the noise, which makes it less useful in practical situations.

Segmentation

A fingerprint image can be segmented into foreground (fingerprint pattern) and background. The segmentation of the image prevents false features from being included in further analysis. The segmentation process is often integrated within the enhancement procedure, thus allowing data obtained by other processing blocks within the algorithm to be efficiently reused. A normalization of the fingerprint image can also be performed to improve the segmentation method. A stand-alone fingerprint segmentation algorithm may be beneficial as a pre-processing step for fingerprint enhancement algorithms with heavy calculation loads, such as [16]. This prevents the background from also being processed. In fingerprint pattern reconstruction methods, the segmentation's role is to outline the area within the image where the fingerprint pattern is recreated [18].

Segmentation based on a sinusoidal wave model within the sub-blocks of each image was proposed in [11]. A fixed size block was classified as recoverable (foreground) or unrecoverable (background). A normalization step on a global level was also proposed to reduce the variance of gray-level values in the image. Normalization on a global level might be unsatisfactory for images with extreme gray-level variations. Thus, a variant operating on a local level of the normalization step, with both fixed and adapted parameters, was proposed in [19]. The segmentation was based on the variance estimated within a block. Blocks with an estimated variance exceeding a preset threshold were considered as foreground. A morphologically based segmentation method with a similar normalization step as in [19] was proposed by [20]. A coherent structure of the orientation field (OF) of ridges and valleys was exploited to outline the segmentation mask in [21]. The linear symmetry used for OF estimation in a pyramid decomposed fingerprint image was reused to segment the fingerprint image in [15]. The energy image derived from block-based short time Fourier transform analysis of a fingerprint image was used to construct the segmentation mask in [14].

There are also stand-alone segmentation methods that are not incorporated within the enhancement methods. A linear classifier was trained on local block features such as cluster degree, mean and variance to distinguish between the foreground and the background in [22]. Morphology was applied as post-processing to minimize miss-classification. The coherence, mean and variance of pixel features on a local level were used to train a classifier for the purpose of fingerprint image segmentation in [23]. Here, the classifier was based on a quadratic surface model trained with the back propagation neural network. Recently, a factorized directional bandpass segmentation method was proposed in [24]. The texture extraction was based on the directional Hilbert transform of a Butterworth bandpass filter with a combination of soft-thresholding.

3.3 Feature Extraction

The type of features used to represent the unique and invariant characteristics of the fingerprint can be categorized into two categories: minutiae- and non-minutiae-based features. Minutiae features are the level 2 features described in section 2.1.

Minutiae points are the most widespread features used for fingerprint matching. Minutiae features carry most of the distinguishing information when extracted from fully captured fingerprints with good image quality. The two minutiae features mostly used are the ridge ending, referred to as termination, and the bifurcation, which refers to a ridge splitting into two ridges. The minutiae are described by the spacial location in the image, their orientation and their type (e.g., termination or bifurcation). The image quality at the location of the minutia can also be specified. However, often only the position and direction of the minutiae are considered in the extracted feature vector. The minutiae features can either be directly extracted from gray-scale images [15, 25], or the fingerprint image is first binarized and thinned before the extraction commences [26]. A minutiae filtering can be performed as a post-processing step to remove doubtful minutiae. This filtering is either performed directly in the gray-scale image or by structural filtering. A local quality measure around the minutiae can also be used with the purpose to exclude doubtful minutiae.

Non-minutiae features are based on local texture, orientation, frequency and ridge shape [27]. These features are preferred in applications when fingerprint sensors with a small sensing area are used since not many minutiae points are captured there. In highly degraded fingerprints, the non-minutiae features might be preferable, due to the difficulty in obtaining a reliable minutiae extraction.

3.4 Feature Matching

The subject of fingerprint feature matching is outside the scope of this thesis. However, to more completely account for how AFIS systems function, an overview of feature matching methods is given in this section. A plethora of fingerprint matching algorithms is presented in [1].

Due to fingerprints' large intra-class variation, feature matching presents a difficult task even with flawless feature extraction (unrealistic). The same finger is able to produce many variants of the captured fingerprint due to the following factors: the displacement and rotation of the finger on the scanner, the change in scale if different scanners are used, and the plasticity of the finger combined with unintended pressure or lack of pressure towards the scanner generating non-linear pattern distortions. In addition, fingerprint scanners with a small sensing area capture only partial fingerprints, resulting in missing features. When possible mistakes in the feature extraction must be considered, the matching phase constitutes a great challenge.

Matching approaches are divided into minutiae- and non-minutia-based, using the feature categorization described in section 3.3. The objective in the minutiae-based matching is to find an alignment between the template and a test minutiae feature set that results in the maximum number of matched minutiae pairs (for identical fingerprints). This approach is often referred to as a point pattern matching problem that can be handled on a global or a local scale. The success of the global minutiae matching greatly depends on the accuracy of the pre-alignment step. In the non-minutiae based matching, the correlation or Euclidean distance is used to calculate the similarity between the features either in the spatial and/or in the frequency domain. Even here, the matching can be done on a global or a local level. Methods where minutiae and non-minutiae features are combined to improve the overall matching also exist.

4 Performance Evaluation

The performance of a fingerprint recognition system is evaluated empirically. The test setup depends on the type of evaluation that is being performed. Each type of performance evaluation involves many variables that need to be handled. For this reason, a standard ISO/IEC 19795 was formulated in an attempt to standardize the evaluation procedure. The ISO/IEC 19795-1 outlines the principles and framework while ISO/IEC 19795-2 addresses the data collection and many of the system errors that can occur during the evaluation.

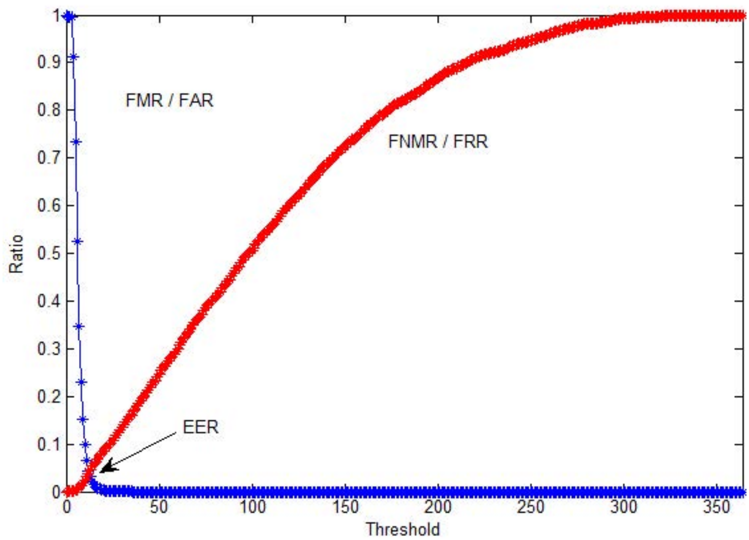
In the academic research literature, the fingerprint verification system type of evaluation is frequently encountered to gauge the performance and improvement of proposed algorithms. The evaluation is based on similarity scores generated by the system between fingerprint pairs. The pairs are divided into genuine and imposter populations. The genuine population consists of fingerprint pairs originating from the same fingertip and which should therefore generate a high similarity score. The imposter population consists of fingerprint pairs originating from different fingertips and which should therefore generate a low similarity score. The results are quantified using specific errors [28] to gauge the performance. These errors are further described in the following.

From the imposter and genuine similarity score distributions, a False Match Rate (FMR) and a False Non Match Rate (FNMR) are calculated. The FMR measures the rate of imposter fingerprint pairs being falsely accepted as a genuine match at a given threshold. The FNMR measures the rate of genuine fingerprint pairs being falsely rejected at a given threshold. In some literature, FMR and FNMR are denoted as False Acceptance Rate (FAR) and False Rejection Rate (FRR), respectively. A difference is, however, that the FAR/FRR errors are generally associated with the verification and identification processes, while FMR/FNMR errors are associated with matching modules in one-to-one comparisons. The point where FMR and FNMR are equal is referred to as the Equal

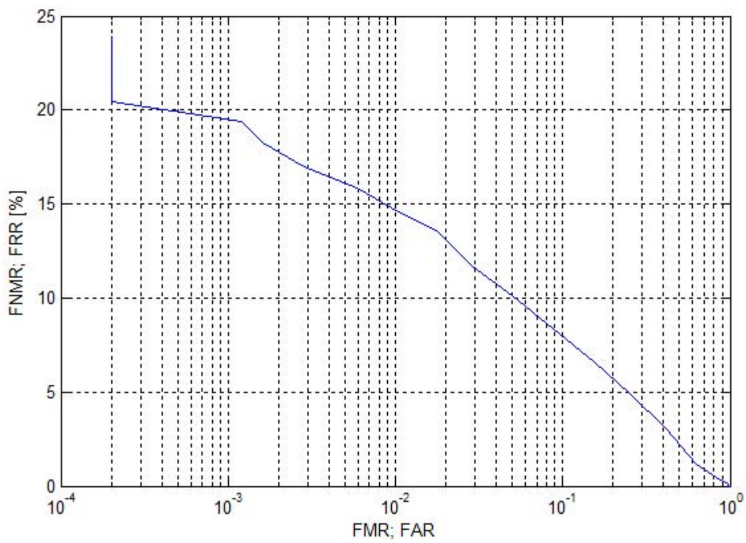
Error Rate (EER), see Fig. 3 a. As the threshold increases, fewer imposters are falsely accepted. However, a higher threshold also increases the false rejection of genuine users. The EER became one of the most popular errors after the Fingerprint Verification Contest (FVC) was held and the results published, see [29]. Since the second and third FVC [30, 31], additional errors evaluating the FNMR when FMR is 1%, 0.1% and 0%, (denoted as FMR100, FMR1000, and ZeroFMR) became widely used. In high-level security applications, fingerprint matching systems often operate far from the EER point to inhibit the FMR. Due to the strict tradeoff between FMR and FNMR, it is therefore of interest to evaluate how the FNMR is affected. Besides these aforementioned errors, a plot of FMR against FNMR denoted as the Detection Error Tradeoff (DET) curve is typically provided. The DET curve depicts the complete error-to-error tradeoff [32]. With FMR in log scale it is easy to read the values of FMR100 (FNMR at 10^{-2}) and FMR1000 (FNMR at 10^{-3}), see Fig. 3 b.

To obtain realistic evaluations, the composition of the test databases needs to represent the conditions in which the AFIS will operate. Gender, age, occupation and geographic location are some of the important factors in conjunction to the collection of database samples or which database should be used to perform specific evaluations. It is also important to use the same evaluation setup when comparing the performance between different AFIS systems, or when modifications are introduced into an existing system.

Within the commercial sector, NIST have performed a large amount of evaluations of different AFIS solutions [33]. Unfortunately, the test databases are often difficult to obtain. Thankfully, with each FVC event, a database with four sub-databases, each sampled with different sensors, have been released. The FVC2000 [34], FVC2002 [35] and FVC2004 [36] databases are easily obtainable and thus popular among researchers. Each sub-database is comprised of an A-set intended for verification and a B-set intended for the tuning of the algorithms. The use of FVC databases and NBIS software [37], for example, allows an objective comparison between fingerprint enhancement methods, (e.g. [16, 15, 14, 38]).



(a)



(b)

Figure 3: a) Typical FMR and FNMR rates and the position of EER, b) Typical DET curve with the FMR in log scale.

5 Research Objectives and Scope

This doctoral thesis focuses on fingerprint matching systems with the aim at contributing to further development in this field. The succeeding research objectives are based on observations founded in literature reviews of published AFIS methods (the confined selection is outlined in section 3). These objectives concisely describe the scope of the thesis.

The two main problems that have been identified to reduce the performance of an AFIS system are as follows:

- The system is used in an environment with a large age variation among the users;
- Matching is performed on fingerprint images of poor quality:

Research Objective I: Design a fully automated enhancement method.
Prior to the feature extraction, the fingerprint image is being pre-processed to enhance the ridge pattern in the image by, for instance, suppressing the background noise. The enhancement is normally done on a local level. A common theme in methods found in literature is that the parameters that dictate the size of the local area are determined beforehand, i.e., they are design parameters. This causes a problem if the method is, for instance, tuned towards an adult population. If so, it will yield a poor performance when having to process fingerprints from children or young adolescents, due to the finer resolution in the ridge pattern that fingerprints from this population produces. To address this issue, the size of the local areas used in the enhancement must be adapted towards each fingerprint. Part I and II address this research objective.

Research Objective II: Focus on the data pre-processing to improve the fingerprint image enhancement. Most enhancement methods rely on an accurate estimation of parameters from local data to yield a good performance. In poor quality fingerprint images, the estimation of parameters used for enhancement is often too inaccurate. Thus, the research presented in Part III addresses the pre-processing of raw data to ensure a more successful enhancement method.

Research Objective III: Develop and evaluate a robust and stand-alone segmentation method. Methods that enhance the quality of fingerprint images increase the overall computational complexity. Segmenting the portion of the image that contains fingerprint pattern from the background forces the enhancement step to only process relevant information, i.e., the fingerprint. Usually, the segmentation process is an integral part of the fingerprint enhancement algorithm where it reuses estimated features from other internal sub-processes. A less complex, stand-alone segmentation method that can be used as a pre-pocessing step is presented in Part IV of this thesis. The introduced method is beneficial since it reduces the computational complexity required by the succeeding enhancement method.

Research Objective IV: Improve the minutiae detection in skeletonized fingerprint images. When extracting fingerprint features, the detection of minutiae points in skeletonized fingerprint images is one of the most popular approaches. Fingerprint images with poor quality typically yield noisy skeleton fingerprints. The crossing number method has been employed to detect minutiae patterns that contain such noise. An attempt to obtain a more robust minutiae detector using a neural network is proposed in Part V and Part VI of the thesis. Due to the increase in computational complexity, the neural network-based minutiae detector is optimized in these thesis parts.

6 Thesis Outline: Summary of Research Contributions

With regard to the previously stated research objectives, relevant contributions made in the form of research publications are presented in the following six parts of the thesis. A brief listing of the main contributions in each part follows.

6.1 Part I: Adaptive Fingerprint Binarization by Frequency Domain Analysis

This paper presents a new approach for fingerprint enhancement by employing directional filters for fingerprint image binarization. The paper proposes a straightforward method for automatically tuning the size of the local area based on analyzing the entire fingerprint image in the frequency domain. The proposed algorithm adjusts adaptively to the characteristics of each local area of the fingerprint image, independent of the characteristics of the fingerprint sensor and the physical appearance of the fingerprint. Frequency analysis is carried out in the local areas to design directional filters for each local area. Experimental results are used to validate the proposed method.

6.2 Part II: Improved Adaptive Fingerprint Binarization

In this paper, improvements to a previous method are presented. Redundant artifacts in a generated fingerprint mask are removed which thereby improves the final result. The proposed method consists of an entirely adaptive process that adjusts to each fingerprint without any user supervision. Hence, the algorithm is insensitive to the characteristics of the fingerprint sensor and the various physical appearances of the fingerprint. Further, the previous method is extended in this part by introducing a detailed description of the fingerprint mask generation. The improved results are validated with experimental data.

6.3 Part III: Adaptive Fingerprint Image Enhancement With Emphasis on Preprocessing of Data

This article proposes several improvements to an adaptive fingerprint enhancement method that is based on contextual filtering. The term adaptive here implies that the parameters of the method are automatically adjusted based on the input fingerprint image. Five processing blocks comprise the adaptive fingerprint enhancement method. The underlying method is based on previous research and four of these blocks have been improved in the proposed system in Part III. Hence, the proposed overall system is novel. The four updated processing blocks involve the following stages: pre-processing, global analysis, local analysis and matched filtering. In the pre-processing and local analysis blocks, a nonlinear dynamic range adjustment method is used. In the global analysis and matched filtering blocks, order statistical filters are applied. These processing blocks yield an improved and new adaptive fingerprint image processing method. The performance of the updated processing blocks is presented in the evaluation of this part. The algorithm is evaluated towards the NIST developed NBIS software for fingerprint recognition on FVC databases.

6.4 Part IV: Adaptive Normalization and Segmentation of Fingerprint Images based on Kurtosis Statistics

This article proposes a novel fingerprint image segmentation method based on local kurtosis statistics. It is well known that sinusoidal signals have a kurtosis value that stands in contrast to other types of signals. A fingerprint pattern resembles a sinusoidal signal on a local scale. Part IV of the thesis exploits these facts by introducing a kurtosis measure on a local level for segmenting fingerprint images from the background. The segmentation method consists of four major parts. First, the fundamental frequency of the fingerprint is estimated. This step is crucial since many parameters, such as the local area size, are dependent on this information. Second, a fully automated fingerprint image normalization is performed. This step compensates for local contrast variation within the image. Third, a kurtosis feature map is estimated from local confined areas within the normalized fingerprint image. The kurtosis feature map is smoothed by order statistical filtering. The fourth and last step involves the generation of a binary segmentation mask by applying a threshold on the smoothed kurtosis feature map. The threshold is determined automatically for each individual feature map and falsely segmented structured background in the binary mask is thereby removed. The proposed segmentation algorithm is evaluated in two separate trials on FVC databases.

6.5 Part V: Neural Network based Minutiae Extraction from Skeletonized Fingerprints

Human fingerprints are rich in details. In this paper, a method of minutiae extraction from skeletonized fingerprint images is proposed. To identify the different shapes and types of minutiae, a neural network is trained to work as a classifier. The proposed neural network is applied throughout the fingerprint skeleton image to locate minutiae. A scheme to speed up the process is also proposed. Using the proposed method, the extracted minutiae can be used as identification marks for automatic fingerprint matching.

6.6 Part VI: Optimization of a Fingerprint Minutia Detector using Statistical Pattern Analysis

In this paper, a patch rejection mechanism for speeding up minutiae detection with a neural network based minutiae classifier is proposed. Key parameters are found through a statistical analysis of fingerprint image patches. The proposed method is evaluated towards FVC fingerprint databases. The proposed method reduces the computational load by 220 times compared to the baseline neural network classifier. The novel analysis provided here shows that a significant performance improvement can be achieved by considering the probabilistic structure of binarized and skeletonized fingerprint image patches.

7 Future Research Directions

An outlook of selected research directions in the context of the presented contributions is given in the following.

- One research direction may combine the work presented in Part III and Part IV of this thesis. A significant reduction of the computational load of the fingerprint enhancement method presented in Part III is obtained if the segmentation step presented in Part IV is performed first. The segmentation mask reduces the number of local areas that need to be processed by the enhancement method. Also, if the analysis in Part III is performed on the normalized fingerprint images from Part IV, the normalization step on the local level in Part III can be omitted. Thus, an additional reduction of the computational load in the fingerprint enhancement method is obtained.
- The kurtosis measure introduced in Part IV for segmentation can also be used as a local fingerprint image quality measure. A research direction may analyze the use of kurtosis as quality indicator as an extension to, for instance, the NIST matcher.
- The so called interoperability problem where cross-sensor feature matching may pose a problem due to different sensor resolution [5] can be solved by using the automated fundamental frequency estimation presented in Part III. A future research direction may include an analysis of the performance improvement for interoperability issues.
- Fingerprint recognition methods do usually not adapt towards each individual fingerprint image. Rather, a set of fixed parameters are chosen in a way that perform well on fingerprints originating from population with similar characteristics (often adults). Thus, a matching of individuals of mixed ages has been shown to be problematic [3, 4]. While the methods proposed in Part I to IV all have the desirable adaptive property, a performance evaluation using these methods on databases with individuals of mixed ages would be of great interest.

The individual parts of the thesis present details to the made contributions. The formatting of the original submitted research papers have been slightly altered to conform to the notations and formatting of this thesis.

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ABSTRACT

Prior to 1960's, the fingerprint analysis was carried out manually by human experts and for forensic purposes only. Automated fingerprint identification systems (AFIS) have been developed during the last 50 years. The success of AFIS resulted in that its use expanded beyond forensic applications and became common also in civilian applications. Mobile phones and computers equipped with fingerprint sensing devices for fingerprint-based user identification are common today.

Despite the intense development efforts, a major problem in automatic fingerprint identification is to acquire reliable matching features from fingerprint images with poor quality. Images where the fingerprint pattern is heavily degraded usually inhibit the performance of an AFIS system. The performance of AFIS systems is also reduced when matching fingerprints of individuals with large age variations.

This doctoral thesis presents contributions within the field of fingerprint image enhancement, segmentation and minutiae detection. The reliability of the extracted fingerprint features is highly dependent on the quality of the obtained fingerprints. Unfortunately, it is not always possible to have access to high quality fingerprints. Therefore, prior to the feature extraction, an enhancement of the quality of fingerprints and a segmentation are performed. The segmentation separates the fingerprint pattern from the background and thus limits possible sources of error due to, for instance, feature outliers. Most enhancement and segmentation techniques are data-driven and therefore based on certain features extracted from the low quality fingerprints at hand. Hence, different types of processing, such as directional filtering, are employed for the enhancement. This thesis contributes by proposing new research both for improving fingerprint matching and for the required pre-processing that improves the extraction of features to be used in fingerprint matching systems.

In particular, the majority of enhancement and segmentation methods proposed herein are adaptive to the characteristics of each fingerprint image. Thus, the methods are insensitive towards sensor and fingerprint variability. Furthermore, introduction of the higher order statistics (kurtosis) for fingerprint segmentation is presented. Segmentation of the fingerprint image reduces the computational load by excluding background regions of the fingerprint image from being further processed. Also using a neural network to obtain a more robust minutiae detector with a patch rejection mechanism for speeding up the minutiae detection is presented in this thesis.

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