Fingerprint Orientation Estimation: Challenges and Opportunities

Amit Kumar Trivedi\textsuperscript{a,*}

\textsuperscript{a}Department of Computer Science and Engineering
Thapar Institute of Engineering and Technology, Patiala, India

Abstract

There is an exponential increase in portable electronic devices with biometric security mechanisms, in particular fingerprint biometric. A person has a limited number of fingerprints and it remains unchanged throughout his lifetime, once leaked to the adversary, it leaks for a lifetime. So, there is a need to secure the biometric template itself. In this survey paper, we review the different security models and fingerprint template protection techniques. The research challenges in different fingerprint template protection techniques are also highlighted in respective sections of the paper. This survey provides a comprehensive study of template protection techniques for fingerprint biometric systems and highlights the challenges and future opportunities.

Keywords: Biometrics, Fingerprint, Orientation, Orientation flow, Biometric template.

1. Introduction

More than a century ago, Alphonse Bertillon conceived the idea of using the measurement of human body to solve the crime related problems [1], but before gaining any popularity, it was replaced by the more significant and practical distinctiveness of the fingerprint. The Home Ministry Office of United Kingdom accepted the individuality of fingerprint in 1893 and used it to identify the person for law enforcement purposes. Many major law enforcement departments started using it to identify the repeated offenders who change their identity after each offense. They started recording the offender fingerprint at the time of arrest and matched against previously recorded fingerprint to identify the repeated offender. Forensic experts also found fingerprints very helpful to identify the criminals by matching the latent fingerprint left at the scene of crime with previously recorded fingerprints. The government law enforcement agencies extensively sponsored the scientific study and development of visual matching techniques for fingerprint matching. They also sponsored training programs for fingerprint experts. The art of fingerprint matching technique was successfully applied to identify the law breakers [2, 3].

Extensive research and training has been accomplished to increase the efficiency and precision of manual fingerprint indexing and matching technique. Due to robustness to forgery, there was a very high demand for fingerprint experts, but the limited number of experts available were not able to cope with the growing demands. The fingerprint indexing techniques based on the Henry system of fingerprint classification generate an extremely skewed distribution of fingerprint in five sets [4]. The training of fingerprint experts was very time consuming and tedious, this made the availability of fingerprint experts very limited, but the demand was very high. All this promoted the research in the area of electronically acquisition of fingerprint data and fully automated fingerprint recognition systems. The dedicated effort of researchers leads to development of Automatic Fingerprint Identification System (AFIS) over the last 5 decades. The low priced and easy availability of highly sophisticated and powerful handheld electronic devices with advanced wireless communication facilities has increased the public concern about information security and identity fraud, resulting in an increase in the demand of fingerprint biometric and other biometric based access control mechanisms for non-forensic applications.

\*Corresponding author

Email address: rivedi19@gmail.com (Amit Kumar Trivedi)
1.1. Biometric Recognition System

The development in electronic circuit manufacturing technology makes it feasible to have very compact yet powerful mobile devices having biometric based access control mechanism. Society is highly connected using these mobile electronic devices with fast and advance communication technologies. In this electronically advanced society, the card or token based person identification or authentication is no more trusted. Information about the card can be stolen and a duplicate card can be made very easily, which is exactly same as the original one. The PIN or password can be easily guessed, knowing some information about the person he/she share on social network. Even the secret password or card can be shared, so they cannot provide security against repudiation [4].

The use of idiosyncratic anatomical or behavioural characteristics, called biometric identifiers or attributes or properties or traits for establishing the individuality of a person for either identification or verification are called Biometric recognition or simply Biometric [4]. Biometric traits cannot be shared or stolen or a duplicate copy cannot be made. They are an intrinsic property of an individual’s physical body or behavior and inseparable from the individual. Establishing the identity of a person both positive and negative from his/her physical body or behavior is very powerful tool for identity management and have immense potential. All these make biometrics a very appealing pattern recognition research problem, but it should be used carefully for the benefit of the society and reduce the identity fraud.

The person identity need to be verified/established at a number of places. Like, is he/she authorized to use some privilege facility or to access privilege information or to check if the person is wanted for some crime, etc.. Some time, to check if the person has already availed the social service or not. Is he/she eligible to avail the services or not? An unreliable answer to these questions may lead to financial or non-financial loss. Biometric identifiers provide a reliable answer to such questions as it cannot be easily forged, shared or lost as compared to traditional token or knowledge based identifiers. Biometric recognition is more convenient, secure, and efficient and hence has better accountability [4]. Fingerprint biometric recognition techniques are being used successfully for law enforcement. The cost of fingerprint sensing device has decreased drastically and can be found in very low-cost hand held devices. Also, the identity fraud or theft for password or token based person identification system has also increased. All these motivated the use of inexpensive fingerprint biometric for person authentication and identification in financial, social welfare, commercial and government domain. Some other biometric traits also find its successful application, but fingerprint has a higher acceptance by users due to its being easy to use.

Biometric system can be used as an identification system or verification system depending on context of its application:

- As an identification system, the biometric system is used to find the identity of the person by matching the captured biometric with the stored biometric template database. The entire template database is searched to find any match with the submitted biometric. It is one-to-many comparison. If a match is found then the corresponding identifier of the enrollment is reported else the subject is not enrolled is reported.

- As a verification system, the biometric system is used to verify the claimed identity by comparing the captured biometric with pre-stored template of a claimed identity. The comparison is one-to-one to confirm whether the claim of identity is true or not. The verification system either rejects or accepts the submitted claim identity.

In the biometric system terminology authentication is used as synonym for verification, but in the information technology terminology authentication is used for both verification and identification. In our proposed research, we are not interested about how the system will be used as verification or identification, so we use a more generic term recognition. A generic block diagram of biometric system in both verification and identification mode is depicted in 1. The enrollment process is common for both modes of operation.

A typical biometric system consists of the following generic processing modules:

- **Biometric sample acquisition module:** In automatic biometric system the biometric sample acquisition is an integral part. A sensor is used to capture the biometric data. The sensor may be digital scanner or a high resolution camera. Sometimes it can have a keyboard to enter some information about the captured sample and a screen to display the information. For fingerprint image capturing generally optical sensor, touch sensor or thermal sensor is used depending on application requirements.
Figure 1: Mode of operation of Biometric system: (a) Enrollment, (b) Verification and (c) Identification
• **Preprocessing module:** The captured raw sample is highly affected by the condition of biometric submitted to the sensor and properties of the sensor itself. So the output of the biometric sample acquisition unit consists of biometric sample plus some unwanted information called noise. These noises need to be removed before extraction of features. The preprocessing highly depend on type of biometric and properties of the sensor. There is no universal process that works for every biometric and sensor. For example the preprocessing of fingerprint biometric cannot be applied to face biometric. The preprocessing of a fingerprint captured by optical sensor will be different from that of the thermal fingerprint sensor.

• **Feature extraction module:** For fast and accurate matching and efficient storage, the raw digital sample need to be processed to extract discriminative features. The accuracy of the system highly depend upon the accuracy of feature extracted. So, this module needs to be optimized to extract features effectively.

• **Template formation module:** A set of features is selected and organized into a form of template to be used by the comparison module for matching or to be stored in the template database for future use.

• **Comparison module:** The comparison module accepts two feature templates, one from the template database and a live template to compute the similarity based on some measurement metrics. It reports match score. The match score is used to take a decision as per threshold of the system. If match score is greater than the threshold, it is called a match otherwise mismatch.

• **Template database:** A specialized database is used to store the templates of biometric sample and any other information about biometric. The type of storage depends upon the application of the biometric system. For example, for identity card, driving license, etc. the template is stored on smart card and for criminal identification the template is stored in crime database.

The system is used to perform one of the following three tasks/processes, namely, **enrollment**, **verification** or **identification**. The enrollment process is common to both verification and identification (see Figure 1). In enrollment process user biometric is being registered with the system. One or more sample is collected using the senor together with some other information as per requirement. From multiple samples the system may select the best sample or may fuse multiple samples. Some time the quality of the sample is also checked for reliability of the sample. The feature extraction module extracts the required features. The template formation module organizes the feature set to form a template which is stored in the template database together with any other information like some unique identifier, name, gender, etc..

The system could work on-line or off-line mode depending on application requirements. For on-line mode of operation the system should be very fast as it requires quick response. Generally for access control mechanism on-line mode is used like in smart phone, computer login, website access etc..

A Fingerprint image has many minute details that are unique to each fingerprint and can be used for identification or verification of a person uniquely. These minute details have same recognizable characteristics as shown in Figure 2. Some of the well recognized features of a fingerprint are minutiae, crossover, core, delta, pore, etc.. The point where two ridges cross each other is called crossover. Generally the point of highest curvature of ridge orientation is termed as core. The ridge ending is called termination minutiae and the point where one ridge divides into two ridges is called bifurcation minutiae. In a fingerprint many different types of features can be identified that are used by the fingerprint expert for matching two fingerprints. But, most of the automated fingerprint recognition system uses only bifurcation and termination minutiae as the extraction of these features can be automated reliably from a low resolution fingerprint image.
Figure 2: The fingerprint image shows the features, which are used by most of the fingerprint authentication/verification systems. Ridge endings are the points where the ridge terminates and at bifurcations ridge divides into two ridges. There are many different types of minutiae like pore, core, delta, etc.. Image taken from http://cnx.org/content/m12574/1.3/ [5], with permission of OpenStax CNX.

2. Fingerprint Representation

A fingerprint image can be represented in one of the four schemes, namely: grayscale image, phase image, skeleton image or minutiae. The minutiae representation is one of the most widely used representation for fingerprint matching, both for a human fingerprint expert and an automated fingerprint recognition system. It is the most compact and distinguishable representation. In the term of performance other representations are better, but are prone to security attack on template database. The grayscale representation scheme or grayscale image contains almost every detailed information of the fingerprint if it was captured with a very high resolution scanner, but it makes the gray scale image the most risky to be stored as templates in insecure database. In comparison to the grayscale image, a phase image and a skeleton image lose all the level 3 features. In comparison to a phase image and a skeleton image, the minutiae template loses all the level 3 and some of the level 2 features.

Figure 3: Fingerprint Representation Schemes [6, 7]: (a) Gray Image, (b) Phase Image, (c) Skeleton Image and (d) Minutiae

The minutiae representation is very compact form of the fingerprint biometric sample. It has sufficient discriminative information to identify a person uniquely, but has very little information that can be used to get the original fingerprint image. Out of the four representations of fingerprint (See Figure 3) the minutiae scheme has the least information and is supposed to be the most secure.

3. Orientation Estimation of Fingerprint

A Fingerprint is composed of ridge lines, which look like curve lines if the width is ignored. The orientation of these curves can be used to remove the irregularity due to noise. The orientation information of the ridges can also be used as a feature. So the efficient and accurate estimation of the orientation of a fingerprint will be very useful.
The angle $\theta_{ij}$, between the small portion of the ridge line centered at $(i, j)$ and horizontal axis is called orientation of the ridge at $(i, j)$. The ridge line does not have an associated start and end point, so it is undirected and values of $\theta_{ij}$ lies in interval $[0, \pi]$. The orientation of the ridge hardly changes at each pixel location, so it is useless to do the computationally expansive work of calculation of orientation for each pixel. Instead, the fingerprint is divided into small square-meshed grid and orientation is estimated for a central pixel of each cell. The matrix composed of these estimated orientations is called orientation image or directional image or orientation map [8], see Figure 4.

| Category                              | Sub-Category | Author          | Year |
|---------------------------------------|--------------|-----------------|------|
| Gradient Based Techniques             |              | Grasselli [8]   | 1969 |
|                                       |              | Stock [9]       | 1969 |
|                                       |              | Kars [10]       | 1987 |
|                                       |              | Mehtre [11]     | 1987 |
|                                       |              | Rao [12]        | 1990 |
|                                       |              | Donahue [13]    | 1993 |
|                                       |              | Rath [14]       | 1995 |
|                                       |              | Kamei [15]      | 1995 |
|                                       |              | Da Costa [16]   | 2001 |
|                                       |              | Bazen [17]      | 2002 |
|                                       |              | He [18]         | 2003 |
|                                       |              | Kamei [19]      | 2004 |
|                                       |              | Nakamura [20]   | 2004 |
|                                       |              | Shertock [21]   | 2004 |
|                                       |              | Jian et al. [50]| 2005 |
|                                       |              | Chikkerur [22]  | 2007 |
|                                       |              | Wang [23]       | 2007 |
|                                       |              | Kekre and Bharadi [24] | 2009 |
|                                       |              | Oliveira [25]   | 2008 |
|                                       |              | Ji [26]         | 2008 |
|                                       |              | Mei et al. [27] | 2009 |
|                                       |              | Babatunde et al. [28] | 2012 |
|                                       |              | Bian et al. [29]| 2014 |

Table 1: Orientation Estimation of Fingerprint
| Category                        | Sub-Category                     | Author                  | Year |
|--------------------------------|----------------------------------|-------------------------|------|
| Reference                      | Orientation Based                | Oliveira [25]           | 2008 |
|                                |                                  | Ji [26]                 | 2008 |
| Using banks of Filters banks   |                                  | Hong [34]               | 1996 |
| Comparing                      | Templates                        | Shmurun et al. [35]     | 1994 |
|                                |                                  | Kawagoe [36]            | 1984 |
| Projection based               |                                  |                         |      |
| Machine Learning Based Techniques| Neural Network                  | Zhu et al. [38]         | 2006 |
|                                |                                  | Ji et al. [26]          | 2008 |
|                                |                                  | Sahasrabudhe [39]       | 2013 |
|                                | Ridge orientation model learning | Ram et al. [45]         | 2009 |
|                                |                                  | Zhang et al. [46]       | 2014 |
|                                |                                  | Zhang et al. [47]       | 2014 |
|                                | Dictionary learning              | Feng et al. [48]        | 2012 |
|                                |                                  | Yang et al. [49]        | 2014 |
|                                |                                  | Jain et al. [50]        | 2015 |
|                                |                                  | Chen et al. [51]        | 2016 |
|                                |                                  | Cao et al. [52]         | 2014 |
|                                |                                  | Liu et al. [53]         | 2017 |
|                                | Markov Model                     | Lee et al. [54]         | 2008 |
|                                | Hybrid                           | Turroni et al. [55]     | 2011 |
| Model Fitting Based            |                                  |                         |      |
|                                |                                  | Sherlock et al. [56]    | 1993 |
|                                |                                  | Vizcaya et al. [37]     | 1996 |
|                                |                                  | Zhou et al. [58]        | 2004 |
|                                |                                  | Gu et al. [59]          | 2004 |
|                                |                                  | Zhou et al. [60]        | 2004 |
|                                |                                  | Li et al. [61]          | 2006 |
|                                |                                  | Li et al. [62]          | 2007 |
|                                |                                  | Huckemann et al. [63]   | 2008 |
|                                |                                  | Gottschlich et al. [64] | 2016 |
|                                |                                  | Wang et al. [65]        | 2007 |
|                                |                                  | Wang et al. [66]        | 2010 |
|                                |                                  | Tashk et al. [67]       | 2009 |
|                                |                                  | Tao et al. [68]         | 2010 |
|                                |                                  | Ram et al. [69]         | 2008 |
|                                |                                  | Ram et al. [70]         | 2010 |
|                                |                                  | Tashk et al. [71]       | 2010 |
|                                |                                  | Jirachaweng et al. [72] | 2011 |
|                                |                                  | Lui and Lui [73]        | 2012 |

Continued...
### 3.1. Gradient Based Techniques

The ridge orientation can be calculated from the gradient values at each pixel value in fingerprint image. The partial-derivatives, \([\nabla_i(i, j), \nabla_j(i, j)]\) represent the gradient at the pixel \([i, j]\) of fingerprint image \(I\). \(\nabla_i\) and \(\nabla_j\) are partial derivatives of \(I\) with respect to \(i\) and \(j\) in respective directions at pixel \([i, j]\). The orientation \(\theta_{ij}\) is calculated as the arctangent of \(\nabla_i/\nabla_j\). This method is very simple, but have two disadvantages: i) discontinuity and non-linearity at \(\pi/2\) and ii) circularity of angle make averaging meaningless.

For solving the above problem of circularity of angles, Kass et al. suggested to double the angles [10]. Based on this idea many efficient methods are proposed for computing the orientation image of fingerprint [12, 14, 17]. Donhue et al. also proposed a method based on gradient independently in 1993 [13]. The perform the least-square minimization for finding the average orientation.

The gradient based orientation estimation fails in a high noise sensitive area where the gradient tends to zero. To solve this problem second order derivatives were suggested [77]. But it solves the problem partially. Da Costa et al. select first or second order derivatives based on the local coherence of the two [16].

The optimum output of different many directional filters in frequency domain (16 numbers of direction filters) were used by [19, 15]. Hong et al. [34] and Nakamura et al. [20] proposed method for spatial domain based on Gabor filter that generate analogous result. Based on Short Time Fourier Transform (STFT) was proposed by Chikkerur et al. [22]. Wang et al. [23] proposed an implementation of gradient-based technique for fingerprint orientation estimation to improve the performance. For each fingerprint image block, the best orientation is chosen from the four overlapping blocks based on the voting of reliability measures. Kekre and Bharadi [24] proposed a gradient based technique and for smoothing the orientation they perform neighborhood averaging. Ali Ismail Awad has presented an implementation of gradient based technique using Graphics Processing Unit (GPU) [78], which was 6.41 times faster than CPU based implementation as claimed by [78]. Dyre and Sumathi presented a gradient based orientation estimation smoothing technique based on analysis of the consistency of orientation in the neighborhood. Abbod et al. [33] divide the fingerprint image into a block of size \(16 \times 16\). Before calculation of the gradient, they applied a Epicycloid shape filter on the target block to mask some pixel.

#### 3.1.1. Reference Orientation Based Techniques

A very simple technique is using \(n\) numbers of reference orientation [4].

\[
\theta_k = k \frac{\pi}{n} \quad (1)
\]

where \(k = 0...n - 1\), and \(n\) is the number of reference orientation. Based on the pixel intensity along the reference orientation \(\theta_{k_{opt}}\) is selected. The local orientation \(\theta_{ij} = \theta_{k_{opt}}\) at the pixel \(I(i, j)\) is computed on a window \(W\) centered at \(I(i, j)\). The sum of pixel intensity along the reference orientation in window \(W\) is minimum and maximum for ridge and valley in the direction of the ridge and valley respectively [9, 11, 18, 25]. The standard deviation of the intensity of the pixels along the reference orientation is calculated and the optimal reference orientation is selected depending on the maximum standard deviation contrast between a reference orientation and its orthogonal orientation [25]. It was suggested by Sherlock [21] to optimized the projection of the ridge line inside the window \(W\) along a number of reference orientation. The reference orientation corresponding to the smallest variation in the projection is taken as orientation of the ridge. Ji et al. modify the above approach by removing the central ridge line before computing the projections [26].

Both gradient based technique and reference orientation based techniques have some advantage and disadvantage. The computational complexity of gradient based technique is less than reference orientation based techniques. In reference based technique, a probability value can be assigned to a different orientation value that may help in the next level of processing to smooth the estimated orientation image.
3.1.2. Comparing Templates

Shmurun et al. [35] presented a template matching technique for construction of the ridge orientation map from a gray image of the fingerprint. They used the radial basis function to reduce the number of base templates. The orientation map was calculated from the contribution of base templates. [36]

3.2. Machine Learning Based Techniques

3.2.1. Neural Network

Nagaty [79] presented a hierarchical neural network of a Back Propagation Network (BPN) and Self-organized Feature Maps (SOFM). BPN was used for feature extraction from blocks of the image and SOFM was used for clustering. The system was robust for noisy fingerprint image. Zhu et al. [38] applied the neural network for the evaluation of correctness of orientation estimated by gradient-based method. The neural network was trained to differentiate between correct and incorrect ridge orientation estimation. The correct orientation of the block around the incorrect orientation block is used for correction of the error. Ji et al. [26] presented a method for calculation of four-direction fingerprint orientation field. They applied Pulse Coupled Neural Network (PCNN) for identification of the primary ridge in a block of fingerprint images. They claimed that the proposed technique is able to achieve the good accuracy on the FCV2004 database with low computational time. For the restoration of noisy fingerprint with the help of orientation map, Sahasrabudhe et al. proposed a orientation estimation technique [39]. They applied two Continuous Restricted Boltzmann Machines (CRBM) to learn the orientation pattern of a fingerprint. The learned orientation field helps the Gabor filter based enhancement algorithm to enhance the noisy fingerprint image.

The well established superiority of the Convolutional Neural Networks (CNN) for pattern classification and the recognition problem inspired Cao et al. [41] to use it for a challenging problem of estimation of the orientation field of latent fingerprint. Schuch et al. [42] applied CNN trained for regression and achieved an RMSE (root mean square error) of 8.53° on noisy data set. Tang et al. [43] presented a Deep Convolutional Network (DCN) that combines the domain knowledge of fingerprint and representation ability of the deep learning algorithm. The proposed technique was able to correctly estimate the fingerprint orientation for both latent and slap fingerprint. Qu et al. design a Deep Regression Neural Network (DRNN) that solve the problem of discontinuity at 0° and the prediction accuracy was high. Wu et al. [40] treated the fingerprint orientation as a multi-classification problem and applied a Support Vector Machine (SVM) to solve it. Their experiment shown that the proposed technique is robust and solve the problem of local noise.

3.2.2. Ridge orientation model learning

Ram et al. [45] develop a statistical model called Active Fingerprint Ridge Orientation Model (AFROM), which can deform according to input. They use Legendre Polynomials to represent the orientation field of fingerprint in the model. The AFROM model can estimate the orientation filed of noisy fingerprint image and also can be used for interpolation and extrapolation. Zhang et al. [46] proposed an Adaptive Orientation Model Fitting algorithm for the estimation of orientation filed for overlapped latent fingerprint. The algorithm was able to separate the orientation of component fingerprint. This work was further extended in [47] to use global orientation field models to predict and correct the orientations in overlapping areas.

3.2.3. Dictionary learning

Inspired by the spelling correction technique used in natural language processing, Feng et al. [48] proposed a fingerprint orientation technique for enhancement of latent fingerprint. They calculate the reference orientation patches from the group of true orientation field and stored in a dictionary. For the estimation of orientation of a fingerprint first orientation of fingerprint estimated using a local orientation technique. Next the estimated orientation field is divided into overlapping patches. For each patch, it’s all six neighbors from the patch dictionary taken as candidate patch. From the candidate patch a final patch is selected based on the compatibility constrain. This technique was further improved in [49] to incorporate pose estimation of latent fingerprint. For pose estimation a Hough transformation based algorithm was used.

The accuracy of the small-scale dictionary is high, but a large-scale dictionary is more robust against noise in fingerprint. Based on this knowledge Chen et al. [51] extended the original work [48] to a multi-scale version. They integrated the estimated orientation at multi-scale to get a better estimated orientation field. They applied multi-layer
Markov Random Field (MRF) model for the formulation and solving the problem. The method proposed in [48] was not good enough to work for fingerprint segmentation and frequency field estimation. To solve this problem Cao et al. [52] proposed a ridge structure dictionary-learning based technique for segmentation and enhancement of latent fingerprint.

3.2.4. Markov Model

A Fingerprint orientation estimation technique based on smoothing of the local ridge structure of fingerprint performance is satisfactory for good quality image, but very poor in low quality region of the image. To solve this problem, Kuang-chih Lee and Salil Prabhakar proposed an orientation estimation technique based on probabilistic technique [54]. They inferred the orientation field from the constructed Markov Random Field (MRF). The proposed MRF composed of two parts. The first part model the global orientation of the fingerprint and the second part enforce the smoothing in local regions.

3.2.5. Hybrid

Mardia et al. [80] first calculate the orientation filed from semi-variogram. This orientation field is quite noisy, local smoothing is required. For smoothing the orientation image, it is first converted to directed vector, then it is processed by a $3 \times 3$ averaging filter. The orientation field so obtained still need some enhancement. They proposed a technique based on Bayesian framework for the enhancement of the estimated orientation filed. Turroni et al. [55] combine the best part of local analysis of orientation and machine learning based global technique to propose an improved fingerprint orientation extraction technique that outperforms the most of the technique on challenging dataset.

3.3. Model Fitting based

Sherlock and Monro presented a mathematical model for computation of the Local Ridge Orientation (LRO) from core and delta positions [56]. Their model has an intelligent tool to resolve the ambiguities in orientation. However, the estimated orientation field differs from the actual orientation filed and has limited practical use. To solve this problem, a nonlinear model was proposed by Vizcaya and Gerhardt [57]. They compared the two models to prove the advantages to their model. A fingerprint orientation model suitable for all types of fingerprints was proposed by Zhao and Gu [58] using rational complex functions.

Gu et al. [59] proposed the polynomial model for global orientation field and a point-charge model for estimation of the orientation field at singularity points. They combined these two models using weighted function to get more robust and accurate fingerprint orientation estimation. Zhou and Gu further improve their work by combining the smoothness except for several singular points [60].

An algorithm was proposed by Li et al. for modeling the fingerprint orientation field [61]. The proposed algorithm comprises of two steps. In first step orientation was predicted for those areas of fingerprint image where ridge information was not available or the coherence of orientation field was low using piece-wise phase partial model. For the second step, a constrained nonlinear phase partial algorithm was proposed. The performance of the proposed technique was tested on the NIST-4 database. It fails only for those fingerprint images where the orientation information cannot be extracted reasonably clearly. This technique was analyzed in [62] for stability. The constrained nonlinear phase partial model [61] fails if two singular points are close. A new model was proposed to deal this problem [62]. The new model has only one constraint which keeps the singularity at the singular points and abandons the first order phase partial constraints.

Based on quadratic differentials, a global model for the fingerprint orientation field was proposed in [63]. For three classes (arches, loops and whorls) different models were designed. Parameters used in the model are invariant under euclidean motions. The model allows extrapolation into unobserved regions of fingerprint images. This work was further extended in [64]. The locally adaptive methods are combined to get more robust global models.

Wang et al. proposed a Fingerprint Orientation Model based on 2D Fourier Expansions (FOMFE) that does not require prior knowledge of singular points [65]. The proposed model can be used to detect singular points. The coefficients FOMFE model can be used as feature vector and fingerprint indexing every effectively.

For partial fingerprint identification, an analytical approach for global ridge orientation modeling based on the inverse orientation model was presented that improve the retrieval rate significantly [66]. Task et al. modified the
FOMFE model using Coherence Matrix for fingerprint ridge orientation estimation [67]. The Coherence Matrix was used to find the uncertainty in the ridge orientation block. This information helps to improve the accuracy of FOMFE. Tao et al. [68] has applied Harris Corner Strength (HCS) for orientation field estimation to remove the abrupt changes in orientation field. The normalized HCF was used as weight in FOMFE method to proposed weighted 2D Fourier expansion (W-FOMFE).

Using Legendre polynomials, a curvature preserving fingerprint ridge orientation smoothing technique was proposed in [69, 70]. Their smoothing technique was based upon the orientation smoothing method proposed by Witkin and Kass [10]. Tashk et al. has used filtering and model based orientation smoothing [71]. For filtering they had applied a Gaussian filter and for smoothing one of the Legendre or Chebyshev type I or II was used depending on the result of filtering stage. Their method does not require the information of singularity points. Jirachaweng et al. [72] first reconstructed the orientation field using lower order Legendre polynomial to get the global orientation. The preliminary orientation pattern was processed in singularity region dynamically using higher order Legendre polynomial.

The fingerprint orientation estimation algorithm needs to perform well in the noisy region in smoothing the orientation filed and also preserve the orientation in the neighborhood of the singularity. Based on weighted Discrete Cosine Transform (DCT), Liu et al. [74] has proposed fingerprint orientation field reconstruction algorithm which performs well in both regions. Bian et al. [29] uses a technique based on quadratic approximation by orthogonal polynomial in two discrete variables for fingerprint orientation field estimation. The Linear Projection Analysis (LPA) is used for estimation of the orientation of local regions. Based on sparse coding and discrete cosine transform, Lui and Lui [73] proposed a fingerprint orientation field model. They use linear combination of sparse coefficient and DCT atoms for orientation field reconstruction.

Gupta and Gupta [75, 76] has proposed a fingerprint orientation field algorithm using a model based technique. The model used in their algorithm is based on the weighted Legendre basis. For ensuring the good performance of the algorithm in both noisy region and in neighborhood of singularity point, they applied three condition on calculation of weight using symmetric filters required for modeling: (i) for preserving the true orientation in neighborhood of singularity points high weight should be assigned in this regions; (ii) in regions of bad quality image (due to scare marks, bruises, sensor noise or finger condition (dry/wet)) should be assigned low weight; and (iii) in the regions of good quality image (uniform ridge-valley flow) should be assigned high weight.

3.4. Perform Evaluation of Orientation Estimation

The performance of fingerprint orientation estimation technique is generally evaluated by measuring the accuracy of singularity points (Core and delta) detected in an orientation image of the fingerprint. The performance of some of the techniques has been also reported as accuracy of fingerprint matching and accuracy of orientation estimation. Some of the very early orientation flow techniques were designed for segmentation of foreground and background of the fingerprint impression and there was not a quantitative evaluation of the performance.

3.4.1. Fingerprint Matching

Fingerprint orientation estimation is one of the fundamental steps in feature extraction for most of the fingerprint biometric system. So, the accuracy of fingerprint matching is directly affected by the accuracy of orientation estimation. The False Match Rate (FMR) and False Non-Match Rate (FNMR) are two widely used measurements to report the performance of fingerprint biometric system. The value where both FMR and FNMR equal is called Equal Error Rate (EER) has been also reported in literature as performance measure for the fingerprint orientation estimation algorithm. In actual application, the fingerprint biometric system does not operate at EER, so other performance metrics like FMR100 or FMR1000 are generally reported. FMR100 is the lowest value of FNMR for FMR is 0.01. Similarly, FMR1000 is the lowest value of FNMR for FMR is 0.001.

3.4.2. Singularity Point Detection

The singularity point (SP) is one of the important feature of a fingerprint, which is invariant to rotation, translation and scaling of the fingerprint. It is generally used for alignment and classification of fingerprints. The Core and delta are two very predominant SP. The Core and delta singularity are in the region of abnormality in orientation flow. So, the accuracy in detection of singularity point (core or delta) can be used as an indirect measure of the accuracy of the fingerprint orientation field estimation algorithms. The performance of some of the orientation flow estimation
technique in term of Precision, Recall and F-measure (Eq. 2, 3 and 4), are also reported by the respective papers for the different standard fingerprint database.

$$\text{Precision} = \frac{TP}{TP + FP}$$ (2)

$$\text{Recall} = \frac{TP}{TP + FN}$$ (3)

$$F - \text{measure} = \frac{2 \times \text{Recall} \times \text{Precision}}{\text{Recall} + \text{Precision}}$$ (4)

where TP, FP, and FN represent true positive (the number of correctly detected SPs), false positive (the number of spuriously detected SPs), and false negative (the number of lost SPs), respectively.

Precision measures the rate of detecting SPs that are the correct ones. Recall describes the proportion of correctly detected SPs. F-measure is the trade-off between Precision and Recall. Well performed FOF estimation will be indicated by good SPs detection where higher values of Precision, Recall and F-measure are achieved.

3.5. Challenges and Opportunity

In Section 3, the classification of different fingerprint orientation flow algorithms is presented together with some important feature of respective algorithm. From the Section 3, it is observed that there is shift from gradient-based and model fitting based techniques toward using machine learning based techniques. This shift can be attributed to the better performance of machine learning based techniques for noisy fingerprint image and partial fingerprint. But, the computational complexity of machine learning based techniques make it unsuitable for large database and portable devices. Non-of-the technique presented in literature is perfect. There is scopes for designing a fingerprint orientation estimation technique having low complexity and good performance. A good orientation estimation can also be used in separation of overlapping latent fingerprints.

References

1. H. T. Rhodes, A. Bertillon, Father of Scientific Detection, Abelard-Schuman, New York, 1956.
2. W. R. Scott, Fingerprint Mechanics: A Handbook, Charles C. Thomas, 1951.
3. R. E. Gaensslen, R. Ramotowski, H. C. Lee, Advances in fingerprint technology, CRC press, 2001.
4. D. Maltoni, D. Maio, A. K. Jain, S. Prabhakar, Handbook of fingerprint recognition, Springer Science & Business Media, 2009.
5. Classification of images, http://cnx.org/content/m12574/1.3/, accessed: 2017-06-06.
6. J. Feng, A. K. Jain, Fingerprint reconstruction: from minutiae to phase, IEEE transactions on pattern analysis and machine intelligence 33 (2) (2010) 209–223.
7. A robust and non-invertible fingerprint template for fingerprint matching system, Forensic Science International 288 (2018) 256 – 265. doi:https://doi.org/10.1016/j.forsciint.2018.04.045.
8. A. Grasselli, On the automatic classification of fingerprints--some considerations on the linguistic interpretation of pictures, in: Methodologies of Pattern Recognition, Elsevier, 1969, pp. 253–273.
9. R. Stock, C. Swonger, Development and evaluation of a reader of fingerprint minutiae, Cornell Aeronautical Laboratory, Technical Report CAL no. XM-2478-X-1 (1969) 13–17.
[10] M. Kass, A. Witkin, Analyzing oriented patterns, Computer Vision, Graphics, and Image Processing 37 (3) (1987) 362 – 385.

[11] B. M. Mehtre, N. N. Murthy, S. Kapoor, B. Chatterjee, Segmentation of fingerprint images using the directional image, Pattern recognition 20 (4) (1987) 429–435.

[12] A. R. Rao, A Taxonomy for Texture Description and Identification, Springer-Verlag, Berlin, Heidelberg, 1990.

[13] M. Donahue, S. Rokhlin, On the use of level curves in image analysis, CVGIP: Image Understanding 57 (2) (1993) 185–203.

[14] N. K. Ratha, S. Chen, A. K. Jain, Adaptive flow orientation-based feature extraction in fingerprint images, Pattern Recognition 28 (11) (1995) 1657–1672.

[15] T. Kamei, M. Mizoguchi, Image filter design for fingerprint enhancement, in: Proceedings International Symposium on Computer Vision, IEEE, 1995, pp. 109–114.

[16] J. P. Da Costa, F. Le Pouliquen, C. Germain, P. Baylou, New operators for optimized orientation estimation, in: Proceedings International Conference on Image Processing, Vol. 3, IEEE, 2001, pp. 744–747.

[17] A. M. Bazen, S. H. Gerez, Systematic methods for the computation of the directional fields and singular points of fingerprints, IEEE transactions on pattern analysis and machine intelligence 24 (7) (2002) 905–919.

[18] Y. He, J. Tian, X. Luo, T. Zhang, Image enhancement and minutiae matching in fingerprint verification, Pattern recognition letters 24 (9-10) (2003) 1349–1360.

[19] T. Kamei, Image filter design for fingerprint enhancement, in: Automatic Fingerprint Recognition Systems, Springer, 2004, pp. 113–126.

[20] T. Nakamura, M. Hirooka, H. Fujiwara, K. Sumi, Fingerprint image enhancement using a parallel ridge filter, in: Proceedings of the 17th International Conference on Pattern Recognition, Vol. 1, IEEE, 2004, pp. 536–539.

[21] B. Sherlock, Computer enhancement and modeling of fingerprint images, in: Automatic Fingerprint Recognition Systems, Springer, 2004, pp. 87–112.

[22] S. Chikkerur, A. N. Cartwright, V. Govindaraju, Fingerprint enhancement using stft analysis, Pattern recognition 40 (1) (2007) 198–211.

[23] Y. Wang, J. Hu, F. Han, Enhanced gradient-based algorithm for the estimation of fingerprint orientation fields, Applied Mathematics and Computation 185 (2) (2007) 823–833.

[24] H. Kekre, V. Bharadi, Fingerprint orientation field estimation algorithm based on optimized neighborhood averaging, in: 2nd International Conference on Emerging Trends in Engineering and Technology, IEEE, 2009, pp. 228–234.

[25] M. Oliveira, N. J. Leite, A multiscale directional operator and morphological tools for reconnecting broken ridges in fingerprint images, Pattern Recognition 41 (1) (2008) 367–377.

[26] L. Ji, Z. Yi, Fingerprint orientation field estimation using ridge projection, Pattern Recognition 41 (5) (2008) 1491–1503.

[27] Y. Mei, H. Sun, D. Xia, A gradient-based combined method for the computation of fingerprints’ orientation field, Image and Vision Computing 27 (8) (2009) 1169–1177.

[28] I. G. Babatunde, A. O. Charles, O. Olatubosun, A block processing approach to fingerprint ridge-orientation estimation, Computer Technology and Application 3 (6) (2012).

[29] W. Bian, Y. Luo, D. Xu, Q. Yu, Fingerprint ridge orientation field reconstruction using the best quadratic approximation by orthogonal polynomials in two discrete variables, Pattern Recognition 47 (10) (2014) 3304–3313.
[30] G. Sulong, et al., A technique to improve ridge flows of fingerprint orientation fields estimation., Telkomnika 14 (3) (2016).

[31] W. Bian, S. Ding, Y. Xue, Combining weighted linear project analysis with orientation diffusion for fingerprint orientation field reconstruction, Information Sciences 396 (2017) 55–71.

[32] H. Li, T. Wang, Y. Tang, J. Wu, P. Yu, L. Guo, J. Chen, Y. Zhang, Combining multi-scale composite windows with hierarchical smoothing strategy for fingerprint orientation field computation, Biomedical engineering online 17 (1) (2018) 136.

[33] A. A. ABBOOD, G. SULONG, A. TAHA, S. U. PETERS, A new technique for estimating and enhancing orientation field of fingerprint image., Journal of Theoretical & Applied Information Technology 96 (7) (2018).

[34] L. Hong, A. Jian, S. Pankanti, R. Bolle, Fingerprint enhancement, in: Proceedings 3rd IEEE Workshop on Applications of Computer Vision, 1996, pp. 202–207.

[35] A. Shmurun, V. Bjorn, S. Tam, M. Holler, Extraction of fingerprint orientation maps using a radial basis function recognition accelerator, in: In Proceedings of 1994 IEEE International Conference on Neural Networks (ICNN'94), Vol. 2, IEEE, 1994, pp. 1186–1190.

[36] M. Kawagoe, A. Tojo, Fingerprint pattern classification, Pattern recognition 17 (3) (1984) 295–303.

[37] B. G. Sherlock, D. M. Monro, K. Millard, Fingerprint enhancement by directional fourier filtering, IEE Proceedings - Vision, Image and Signal Processing 141 (2) (1994) 87–94. doi:10.1049/ip-vis:19949924.

[38] E. Zhu, J. Yin, C. Hu, G. Zhang, A systematic method for fingerprint ridge orientation estimation and image segmentation, Pattern recognition 39 (8) (2006) 1452–1472.

[39] M. Sahasrabudhe, A. M. Namboodiri, Learning fingerprint orientation fields using continuous restricted boltzmann machines, in: 2nd IAPR Asian Conference on Pattern Recognition (ACPR), IEEE, 2013, pp. 351–355.

[40] Y. Wu, T. Zhao, S. Wang, A. Yong, T. Guo, A svm-based method for the estimation of fingerprint and palmprint orientation, in: Fourth International Conference on Intelligent Control and Information Processing (ICICIP), IEEE, 2013, pp. 343–348.

[41] K. Cao, A. K. Jain, Latent orientation field estimation via convolutional neural network, in: 2015 International Conference on Biometrics (ICB), IEEE, 2015, pp. 349–356.

[42] P. Schuch, S.-D. Schulz, C. Busch, Convnet regression for fingerprint orientations, in: Scandinavian Conference on Image Analysis, Springer, 2017, pp. 325–336.

[43] Y. Tang, F. Gao, J. Feng, Y. Liu, Fingernet: An unified deep network for fingerprint minutiae extraction, in: 2017 IEEE International Joint Conference on Biometrics (IJCB), IEEE, 2017, pp. 108–116.

[44] Z. Qu, J. Liu, Y. Liu, Q. Guan, C. Yang, Y. Zhang, Orienet: A regression system for latent fingerprint orientation field extraction, in: International Conference on Artificial Neural Networks, Springer, 2018, pp. 436–446.

[45] S. Ram, H. Bischof, J. Birchbauer, Active fingerprint ridge orientation models, in: International Conference on Biometrics, Springer, 2009, pp. 534–543.

[46] N. Zhang, X. Yang, Y. Zang, X. Jia, J. Tian, Overlapped fingerprints separation based on adaptive orientation model fitting, in: 22nd International Conference on Pattern Recognition, IEEE, 2014, pp. 678–683.

[47] N. Zhang, Y. Zang, X. Yang, X. Jia, J. Tian, Adaptive orientation model fitting for latent overlapped fingerprints separation, IEEE Transactions on Information Forensics and Security 9 (10) (2014) 1547–1556.

[48] J. Feng, J. Zhou, A. K. Jain, Orientation field estimation for latent fingerprint enhancement, IEEE transactions on pattern analysis and machine intelligence 35 (4) (2012) 925–940.
[49] X. Yang, J. Feng, J. Zhou, Localized dictionaries based orientation field estimation for latent fingerprints, IEEE transactions on pattern analysis and machine intelligence 36 (5) (2014) 955–969.

[50] A. K. Jain, K. Cao, Fingerprint image analysis: role of orientation patch and ridge structure dictionaries, Geometry driven statistics 121 (288) (2015) 124.

[51] C. Chen, J. Feng, J. Zhou, Multi-scale dictionaries based fingerprint orientation field estimation, in: International Conference on Biometrics (ICB), IEEE, 2016, pp. 1–8.

[52] K. Cao, E. Liu, A. K. Jain, Segmentation and enhancement of latent fingerprints: A coarse to fine ridgestructure dictionary, IEEE transactions on pattern analysis and machine intelligence 36 (9) (2014) 1847–1859.

[53] S. Liu, M. Liu, Z. Yang, Sparse coding based orientation estimation for latent fingerprints, Pattern Recognition 67 (2017) 164–176.

[54] K. Lee, S. Prabhakar, Probabilistic orientation field estimation for fingerprint enhancement and verification, in: Biometrics Symposium, IEEE, 2008, pp. 41–46.

[55] F. Turroni, D. Maltoni, R. Cappelli, D. Maio, Improving fingerprint orientation extraction, IEEE Transactions on Information Forensics and Security 6 (3) (2011) 1002–1013.

[56] B. G. Sherlock, D. M. Monro, A model for interpreting fingerprint topology, Pattern recognition 26 (7) (1993) 1047–1055.

[57] P. R. Vizcaya, L. A. Gerhardt, A nonlinear orientation model for global description of fingerprints, Pattern Recognition 29 (7) (1996) 1221–1231.

[58] J. Zhou, J. Gu, Modeling orientation fields of fingerprints with rational complex functions, Pattern recognition 37 (2) (2004) 389–391.

[59] J. Gu, J. Zhou, D. Zhang, A combination model for orientation field of fingerprints, Pattern recognition 37 (3) (2004) 543–553.

[60] J. Zhou, J. Gu, A model-based method for the computation of fingerprints’ orientation field, IEEE transactions on image processing 13 (6) (2004) 821–835.

[61] J. Li, W.-Y. Yau, H. Wang, Constrained nonlinear models of fingerprint orientations with prediction, Pattern Recognition 39 (1) (2006) 102–114.

[62] J. Li, W.-Y. Yau, J. Wang, W. Ser, Stability analysis of constrained nonlinear phase portrait models of fingerprint orientation images, in: International Conference on Biometrics, Springer, 2007, pp. 493–502.

[63] S. Huckemann, T. Hotz, A. Munk, Global models for the orientation field of fingerprints: an approach based on quadratic differentials, IEEE Transactions on Pattern Analysis and Machine Intelligence 30 (9) (2008) 1507–1519.

[64] C. Gottschlich, B. Tams, S. Huckemann, Perfect fingerprint orientation fields by locally adaptive global models, IET Biometrics 6 (3) (2016) 183–190.

[65] Y. Wang, J. Hu, D. Phillips, A fingerprint orientation model based on 2d fourier expansion (fomfe) and its application to singular-point detection and fingerprint indexing, IEEE Transactions on Pattern Analysis and Machine Intelligence 29 (4) (2007) 573–585.

[66] Y. Wang, J. Hu, Global ridge orientation modeling for partial fingerprint identification, IEEE transactions on pattern analysis and machine intelligence 33 (1) (2010) 72–87.

[67] A. Tashk, M. S. Helfroush, M. Muhammadpour, Improvement of fingerprint orientation estimation by a modification of fingerprint orientation model based on 2d fourier expansion (m-fomfe), in: 2009 2nd International Conference on Computer, Control and Communication, IEEE, 2009, pp. 1–6.
[68] X. Tao, X. Yang, K. Cao, R. Wang, P. Li, J. Tian, Estimation of fingerprint orientation field by weighted 2d
fourier expansion model, in: 20th International Conference on Pattern Recognition, IEEE, 2010, pp. 1253–1256.

[69] S. Ram, H. Bischof, J. Birchbauer, Curvature preserving fingerprint ridge orientation smoothing using legen-
dre polynomials, in: 2008 IEEE Computer Society Conference on Computer Vision and Pattern Recognition
Workshops, IEEE, 2008, pp. 1–8.

[70] S. Ram, H. Bischof, J. Birchbauer, Modelling fingerprint ridge orientation using legendre polynomials, Pattern
Recognition 43 (1) (2010) 342–357.

[71] A. Tashk, M. S. Helfroush, M. J. Dehghani, A chebyshev/legendre polynomial interpolation approach for finger-
print orientation estimation smoothing and prediction, Journal of Zhejiang University Science C 11 (12) (2010)
976–988.

[72] S. Jirachaweng, Z. Hou, W.-Y. Yau, V. Areekul, Residual orientation modeling for fingerprint enhancement and
singular point detection, Pattern Recognition 44 (2) (2011) 431–442.

[73] S. Liu, M. Liu, Fingerprint orientation modeling by sparse coding, in: 5th IAPR International Conference on
Biometrics, IEEE, 2012, pp. 176–181.

[74] M. Liu, S. Liu, Q. Zhao, Fingerprint orientation field reconstruction by weighted discrete cosine transform,
Information Sciences 268 (2014) 65–77.

[75] P. Gupta, P. Gupta, Fingerprint orientation modeling using symmetric filters, in: IEEE Winter Conference on
Applications of Computer Vision (WACV), IEEE, 2015, pp. 663–669.

[76] P. Gupta, P. Gupta, An accurate fingerprint orientation modeling algorithm, Applied Mathematical Modelling
40 (15-16) (2016) 7182–7194.

[77] K. G. Larkin, Uniform estimation of orientation using local and nonlocal 2-d energy operators, Optics Express
13 (20) (2005) 8097–8121.

[78] A. I. Awad, Fast fingerprint orientation field estimation incorporating general purpose gpu, in: Soft Computing
Applications, Springer, 2016, pp. 891–902.

[79] K. A. Nagaty, On learning to estimate the block directional image of a fingerprint using a hierarchical neural
network, Neural Networks 16 (1) (2003) 133–144.

[80] K. V. Mardia, A. Baczkowski, X. Feng, T. Hainsworth, Statistical methods for automatic interpretation of digi-
tally scanned finger prints, Pattern Recognition Letters 18 (11-13) (1997) 1197–1203.