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A Survey on State of the Art Methods of Fingerprint Recognition

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ABSTRACT

Fingerprint recognition is one of the most well-known and publicized biometrics for personal identification and authentication. With the advancement of technology and for security purposes in various civilian, defence and commercial applications, fingerprint recognition is studied since a long time. Since second millennium BCE when fingerprints were used as signature, researchers have done studies on different aspects and features of fingerprint. This paper specifies a literature survey of the widely used techniques in fingerprint recognition system. Some of the renowned techniques of feature extraction and matching modules are discussed in deep.

Keywords: Fingerprint recognition, Minutiae points, Fingerprint classes

I. INTRODUCTION

Biometrics technologies are automated methods which uses physiological or behavioural characteristic of an individual for verifying or recognizing the identity of a living person [1], [2], [3], [4]. Fingerprint [5], face, voice, iris [2], retina geometry [6], palm print [7], gait, hand vein [8], signature etc. are popular biometric characteristics [9] widely used in automatic identification of individuals [10]. Among them, fingerprint recognition is most reliable biometric due to its uniqueness among the people, stability, originality and fairly good performance in terms of accuracy, speed and robustness [11].

Fingerprint identification is one of very few techniques employed in forensic science for criminal investigation as FBI uses fingerprints to store data and records of criminals [12] . Also it is used in legal affairs as it can be used as evidence on legal documents in place of signature [13]. In safeguarding work [14] such as providing protection to health, wealth and human rights, fingerprint recognition system has been used in doors and lockers. National IDs' such as unique ID, passports use fingerprint to identify an individual. Real time Automated Personal IDentification System (RAPIDS) at DoD (Department of Defence in USA) [15] uses fingerprint for personal identification.

Fingerprint recognition is used in numerous applications that include civilian and commercial applications like military, law enforcement, medicine, education, payment using ATM [16], civil service, forensics [14], driving license registration, cellular phone access, computer log-in [16].

As discussed in [17], fingerprint identification began in the late 19th century with the development of identification bureaus for storage and verification of criminal records using any physiological characteristic instead of names. Slowly, the focus shifted from verification to identification of a single person from a large database [18].

Fingerprint impression of a person consists of ridges (black lines) and valleys (white region) [19]. A ridge can spread into two ways: ridge ending and ridge bifurcation. Combination of ridge ending and ridge bifurcation is called basic Minutiae points [19]. Figure 1 shows a sample fingerprint consisting of minutiae points.

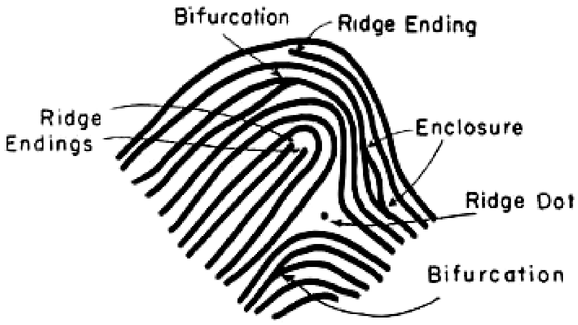

Figure 1. Minutiae points in sample fingerprint

Fingerprint of a person contains numerous distinctive features which makes them unique from a person to person. Figure 2 shows that fingerprint features can be classified mainly as three levels [4], [20] :

1) Level 1 (Global): refers ridge flow patterns (orientation) and singular points such as core and delta.

2) Level 2 (Local): introduces minutiae details such as ridge ending and ridge bifurcation.

3) Level 3 (Fine details): includes intra-ridge details such as width, shape, curvature, edge contours and even sweat pores.

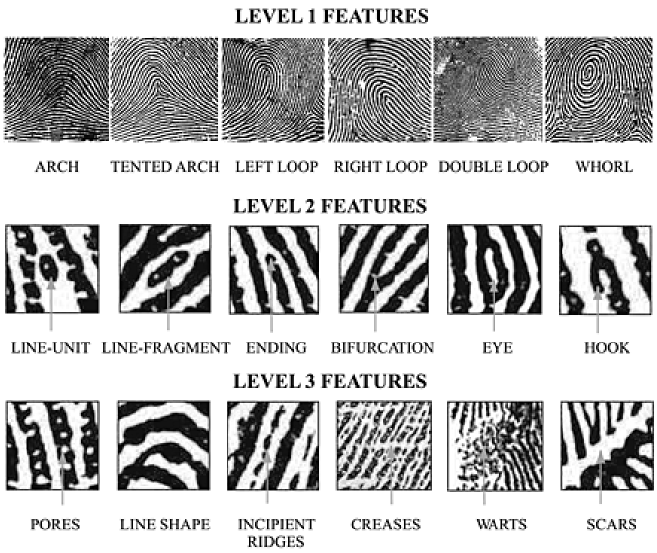

Figure 2. Feature classification

Among these different levels of features, level 1 feature can be used for fingerprint classification as they are defined from global charac2teristics. Level 2 and 3 features are commonly used for fingerprint matching [21] as they allow to claim for the individuality of a fingerprint. Once features are classified, the fingerprint pattern can be classified in six common classes [19]:

1) Arch: ridges enter from one side, rise to form a small bump, and then go down and to the opposite side. No loops or delta points are present.

2) Tented Arch: similar to the arch except that at least one ridge has high curvature, thus one core and one delta points.

3) Left loop: one or more ridges enter from one side, curve back, and go out the same side they entered. Core and delta are present.

4) Right loop: same as the left loop, but different direction.

5) Whorl: contains at least one ridge that makes a complete 360 degree path around the centre of the fingerprint.

6) Unclassified: Fingerprints in databases are non-uniformly distributed in these classes. Fig. 3 shows above 6 classes of fingerprint.

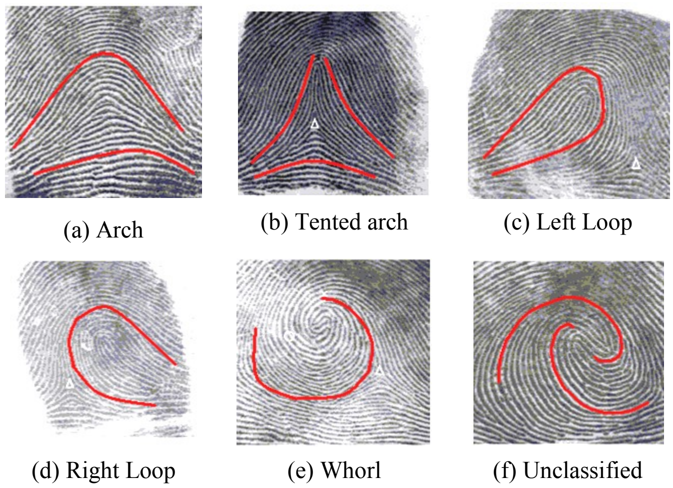

Figure 3. Fingerprint classes

Conventional fingerprint recognition system consists of 3 main sub-domains [22]: Image acquisition and pre-processing; Feature extraction and Matching/ Classification. Fingerprint images are acquired by the sensors adopted by the system or mobile device. These acquired images are pre-processed to improve the quality of image. Pre-processing such as image enhancement and morphological operations such as thinning, thickening etc. is done on the images. Popular enhancement techniques are directional median filter [23], directional weighted median filter [24] and STFT analysis [25].

Minutiae features such as ridge ending and bifurcations are extracted after refining of the thinned image and detecting the minutiae points. Additional features such as core, delta, island, pores, crossovers etc. can also be detected to improve the matching process [26]. The most popular technique of minutiae detection is through the use of the crossing numbers approach [22]. Gabor filter is also used for feature extraction [27]. Once the features are extracted from fingerprint image, matching is performed with already registered template or by machine learning techniques. Matching score is computed using score computation metrics and performance evaluation is done using performance metrics. Main modules of fingerprint recognition system are shown in Figure 4.

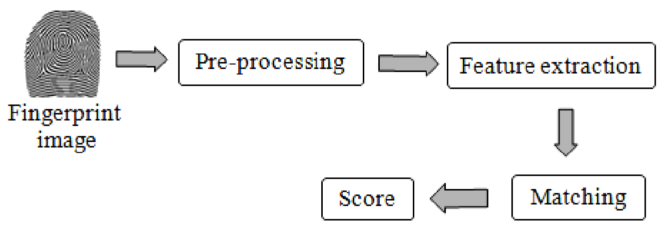

Figure 4. Main modules of fingerprint recognition system

Fingerprint matching includes numerous techniques according to extracted features used for matching and in terms of processing. Among them there are mainly two types: minutiae-based approach and non-minutiae based approach. Non-minutiae based approach [28], [29] includes Image-based method, Ridge-feature based method, Level3 feature based method and feature-point-based method. Minutiae-based method [20] includes local minutiae matching and global minutiae matching. Techniques also use hybrid approach [29], [30] in which combination of minutiae features and non-minutiae features are combined to improve accuracy since only minutiae features may not be sufficient for matching [31].

Image-based method [30], [32], [33], [34] is a non-minutiae based technique that directly compares the entire fingerprint patterns by finding the correlation between two images but this method is vulnerable to the alignment error caused by non-linear deformation. Texture features such as Gabor response [30], [32], Local Binary Pattern (LBP) [33], Histogram of Oriented Gradient (HoG) [34] are also used which is also sensitive to noise, skin condition or nonlinear deformation.

This problem of nonlinear deformation can be solved by using Ridge-feature-based approaches that utilize the topological information of the ridge patterns which includes ridge orientation [35] and frequency [36] information but the problem with this method is only several ridges of minutiae are used in extraction and ridge information cannot be used sufficiently for matching. For validating the usefulness of ridge features, Level3 feature based method is used which incorporates ridge details such as pores [28], dots and incipient ridges [37] and ridge contours along with minutiae features to improve performance. However these features can only be detected in high-resolution fingerprint images of 1000 dpi and over. Several researches proposed partial fingerprint matching based on Scale Invariant Feature Transform (SIFT) [38] or accelerated KAZE (AKAZE) [39], [40] features which are typically used for object recognition and image matching these approaches are relatively sensitive to the large textural variations caused by noise or skin condition. Table I show non-minutiae based fingerprint recognition methods and features used in each of them.

Table 1. Non-Minutiae Based Fingerprint Recognition Methods

Method	Features
Image-based method	Pixel intensities [30]; Texture features such as Gabor response [30] [32], LBP [33], [41], HoG [34]
Ridge feature-based method	Ridge orientation [35], Ridge frequency [36], Ridge count [42]
Level 3 feature-based method	Pores [28], Dots and incipient ridges [37], Ridge contour
Feature-point-based method	Key-points such as SIFT [38], A-KAZE [39], [40]

The organization of this document is as follows. In Section 2 (Survey of existing methods) discussion of various state of the art methods of pre-processing and feature extraction in fingerprint recognition system is given. Finally, in Section 3 (Conclusion and discussion) the paper is concluded and suggests the future work.

II. SURVEY OF EXISTING METHODS

Survey of various techniques of pre-processing and feature extraction modules of fingerprint recognition is discussed in this section.

A. Pre-processing

Images captured by different sensors may contain various noises, false traces, blurred ridges and indistinct boundaries [43] which may result in poor quality images. Hence before proceeding for matching images need to be pre-processed which includes noise reduction, contrast enhancement, improving contrast among ridges and valleys of grayscale fingerprint pictures and morphological operations [44]. Fingerprint enhancement can be conducted on either binary ridge images or gray-scale images thus Input image is normalized so that it has a pre-specified mean and variance. In [45] two approaches are described for fingerprint image enhancement: Spatial Domain Method, which operates directly on pixels and Frequency Domain Method, which operates on Fourier transfer of an image.

Histogram equalization (HE) is most extensively utilized global contrast enhancement technique due to its simplicity and ease of implementation [46] which distributes the pixel values uniformly such that the enhanced image has linear cumulative histogram. This technique is used to make the intensity distribution uniform by re-assigning the intensity values of pixels and effectively spreading out the most frequent intensity values across the entire spectrum of pixels (0-255) [47]. Through this adjustment, the intensities can be better distributed on the histogram and lower local contrast can gain a higher contrast.

Directional Median Filter (DMF) [23] can be used for reducing Gaussian distributed noises (by anisotropic filter) and impulse noises along the direction of ridge flow (by DMF). This algorithm may fail when image regions are contaminated with heavy noises and orientation field in these regions can hardly be estimated. An improved method was proposed in [24] over [23] that is Directional Weighted Median Filter (DWMF). A new impulse detector [24], which is based on the differences between the current pixel and its neighbors aligned with four main directions. It is appropriate to use Gabor filters as band pass filters to remove the noise and preserve true ridge/valley structures as Gabor filters have both frequency-selective and orientation-selective properties and have optimal joint resolution in both spatial and frequency domains [48]. In [49], it is stated that the previous fingerprint image enhancement methods based on Traditional Gabor filter (TGF) banks have some drawbacks in their image-dependent parameter selection strategy, which leads to artifacts in some cases. To overcome this issue, modified Gabor filter (MGF) have been developed as an improved version of the TGF. Its parameter selection scheme is image-independent.

Fourier transform [3] is an important mathematical tool used to decompose an image into sine and cosine components that divide the fingerprint image into small processing blocks and enhance each block independently. Wavelet transform is an effective tool in reducing noise in which images are analyzed at multiple scales [43], [50]. Directional Wavelet Transform (DWT) [50], [51] can be used for image enhancement and noise removal. DWT along with Gabor filter is also recommended for noise removal. Gabor wavelet filter bank (GWT) and Directional Median Filter (DMF) together used as robust approach to fingerprint image enhancement. Gaussian-distributed noises are reduced effectively by Gabor Filters and impulse noises by DMF. Short Time Fourier Transform (STFT) is a new approach for fingerprint enhancement which is a well known technique in signal processing to analyze non-stationary signals [25]. This algorithm estimates all the intrinsic properties of the fingerprints such as the foreground region mask, local ridge orientation and local ridge frequency.

Directional filter bank [52] reduces the influence of noise on the ridges and valleys, enhances the ridges' moving shape and preserves the spatial characteristics at minutiae and singular points. In [53], minutiae can be directly extracted from gray-level fingerprint images. Their algorithm is based on a gray-level ridge tracing [54] which extracts ridges by sequentially following each gray-level ridge until it ends or bifurcates. Their algorithm does not binarize the gray-level fingerprint image directly when conducting minutiae extraction, but binarization is still conducted implicitly by the gray-level ridge tracer. The problem of binarization of gray-level images [55] by Blayvas I et al. by acquiring images under non-uniform illumination and using different method to determine an adaptive threshold surface which gives faster binarization and better performance..

Captured fingerprint contains two components, original area captured by contacting the sensor called foreground and noisy are at the borders called background. Fingerprint segmentation [20] is used to separate two areas of fingerprint called foreground and background from each other and also for removing false features. A segmentation algorithm in [56], based on pixels features, using the criterion of Rosenblatt's perceptron to classify the pixels. The disadvantage of this algorithm is based on pixels features and moderate performance which gives low speed. N. Ratha, et al. [57] used morphological operators to detect and remove spikes.

B. Feature Extraction

Different levels of features can be extracted using feature extraction techniques according to the matching technique used. Singular points are extracted by its symmetry properties using symmetry point extraction as proposed in [58]. Complex orientation field is used to in which complex filters are conducted in multiple resolution scales. The symmetry is detected by its strong response to complex filters [59].

PoinCare Index (PI) [40], [60], [61] is a popular method to detect singular points which is computed as the sum of the difference between the orientation of point and each of its neighbor [62]. Depending upon value of PI singular points can be detected whether it is core or delta. However a challenging task is to improve reliability of orientation field as wrong orientation of points due to noise or poor quality of image can result in spurious detection. Chikkerur and Ratha [60] presented significant improvements in singular point detection algorithm based on complex filtering principles originally proposed by Nilsson and Bigun in [63]. J. Zhou et al. [61] proposed to use the DORIC (Differences of the ORIentation values along a Circle) feature for singular point verification, which can remove spurious detections and provide more discriminative information. The method needs more heuristics and sophisticated filters to detect singular points [62].

Convolution Neural Network (CNNs) [31], [62] are biologically inspired variants of multilayer perceptrons (MLP) [64], used to automatically detect singular points with lack dependence of any prior knowledge and human effort. In [62], a two layer CNN feature extraction and non-linear classifier is used for singular point detection by learning Multi-Stage (MS) features using CNN architecture provided by D. Sermanet et al. in [65] which provides richer complementary information such as local textures and fine details. A deep CNN is employed in [31] to learn global and minutiae features followed by K-Nearest Neighbor policy for proper triplet selection. S. Kim et al. [13] proposed a fingerprint liveness detection method based on a deep belief network (DBN) in which features are learned by Convolution network with random filters followed by the Principle Component Analysis (PCA). In [66], a convolution network is used to extract features, whose dimension is reduced by the principal component analysis (PCA), to be used by a SVM for fingerprint liveness detection.

Crossing numbers (CN) [22], [54], [67] are the most commonly employed method of minutiae extraction concept. Rutovitz's definition for crossing number involves the use of the skeleton image where the ridge flow pattern is eight-connected which extracts both true and false minutiae [54] where H-point elimination method to remove several types of spurious minutiae. In [22], an advancement of crossing number is used from which ridge ending and bifurcation can be detected using threshold value of CN and from applying it, 24 possible bifurcation templates are generated for ease in extraction. Applying same to the algorithm after image enhancement step, M. M. Min et al. [67] proposed 8 different possible termination and bifurcation features.

Gabor filter are used in the region around the fingerprint core point in a well-known image-based feature extraction technique, FingerCode [68] to extract local and global features which computes the standard deviation from mean of grey levels to define feature vector. The main problem of this approach is detection of a reliable core. In [69], [70] two FingerCode variants are proposed, where fingerprints are first zaligned using minutiae before extraction In [69] a set of 8 Gabor filters are used for hybrid approach of minutiae and ridge flow information to capture ridge strength at equally spaced orientation whereas 2D wavelet decomposition and convolution with 16 Gabor filter are used for extracting fingerprint pattern and minutiae in [70]. These hybrid approaches [68], [69], [70] tend to give better results than conventional minutiae-based fingerprint matching. L. Nanni et al. [33] proposed a hybrid approach where fingerprints are pre-aligned using minutiae, and then image-based features are extracted by invariant local binary patterns (LBP) from the fingerprint image convolved with Gabor filters which together called GLBP (combination of Gabor filter and LBP). Here, Gabor filter is applied on different wavelet sub-bands [70] and invariantly LBP [33] to show that combining descriptors may improve the discrimination power.

Local Binary Pattern (LBP) operator is used for feature extraction in [41] to get LBP histogram on extracted pores and calculate the chi-square distance between two average LBP histograms is performed for matching that gives the best match. [41] Combines the pore-LBP based level-3 matching score and minutiae-based level-2 matching score in decision level. Local Phase Quantization (LPQ) [71] is statistics of labels computed in the local pixel neighborhoods through filtering and quantization. These methods describe each pixels neighborhood by a binary code which is obtained by first convolving the image with a manually predefined set of linear filters and then binarizing the filter responses. The bits in the code string correspond to binarized responses of different filters. As proposed in [71], BSIF is inspired by LBP and LPQ to automatically learn a fixed set of filters from a small set of natural images, instead of using handcrafted filters such as in LBP and LPQ.

Minutiae Cylindrical Code (MCC) [21] uses the Minutia Cylinders to code the fingerprint into fixed length using binary representation. The algorithm proposed in [72] uses binary minutia cylinder code (MCC) as minutia descriptor which encodes locations and directions of neighbor minutiae around each minutia into a fixed-length bit vector. MCC is more accurate and robust than minutia triplets, but its dimensionality is higher.

Locality Sensitive Hashing (LSH) is effective and efficient in finding approximate nearest neighbor of high-dimensional vector [73]. Locality Sensitive Hashing (LSH) is used to efficiently find out hypothesis correspondences of MCC instead of traditional quantization scheme. An improved Locality Sensitive Hashing algorithm for MCC descriptor is proposed in [74] combining with pose estimation algorithm.

Minutiae Vicinity (MV) was proposed by Guoqiang Li et al. in [75]. A minutiae vicinity is a fundamental unit which is framed by four details including an inside minutia and its three nearest neighboring details sorted by climbing request in view of their Euclidean distance with inside minutia. Minutiae Vicinity (MV) and Minutiae Cylinder Code (MCC) both are used in score level fusion method [75], [76] for fingerprint indexing approach where matching is quite complex for a large database. In [75] new designed indexing method extracts a feature vector including 9 components from minutiae details and a triplet which is contained in a Minutiae Vicinity. In [76], it is proposed that MV- features and MCC-Features are extracted from the sample. After extraction these features are fused and a single feature vector or a template is obtained. Principal component analysis (PCA) [35], [66] is a powerful algorithm used for dimensionality reduction of the data to make the algorithm faster and more efficient.

M. Yamazaki et al. [38] adopts scale invariant feature transform (SIFT) for partial fingerprint matching. Gaussian blurring causes ridges diffusion, which reduces the distinctiveness of fingerprint texture. Mathur at el. [39] applies A-KAZE feature to address this problem. A-KAZE features use non-linear diffusion, which preserves fingerprint ridges. Histogram of Gradients (HoG) [34] is an image-based matcher proposed by N. Dalal et al. [77] where the histogram of gradients features are used to describe the fingerprint which represent an image is represented by a set of local histograms which count occurrences of gradient orientation in a local cell of the image gives best results for stand-alone descriptors as it outperforms Gabor filters and LBP [34]. Inspired by histograms of oriented gradients (HOG) and the scale invariant feature transform (SIFT), a new approach of Histogram Invariant Gradient (HIG) is proposed in [78] which achieves average accuracy for liveness detection.

As various techniques are used for fingerprint recognition depending on the extracted features, each technique has different aspects and metrics. A comparative study of widely used existing methods is shown in Table 2.

Table 2. Survey On Various Fingerprint Recognition Methods

Ref.	Technique	L/G	Features	No of thumb Fingerprints used	Database Used	Minutiae extraction	Classifier	Accuracy
[4]	Multi-feature based score fusion method	L	Minutiae + texture information (Ridge count)	48 people with 10 impressions of each finger	FVC 2000 DB1 FPC DB	Traditional minutiae-based matching method	Hausdorff distance	Matching score: 4.57% 2.04% 97.05% boost EER: Lower than 50% for all
[29]	Partial fingerprint-matching method incorporating new RSFs with minutiae	L	Minutiae + edge shapes (concave and convex) are	-	FVC20 02, FVC20 04 and BERC	Local neighborhood of minutiae (Ridge shape features RSF) Proposed algorithm	Euclidean distance	-
[74]	Minutiae – based indexing with pose constraint	L	Ridge orientation information	-	FVC2000 DB1 FVC2000 DB2 FVC2000 DB3 NIST Special Database 4 NIST Special Database 14	local 1-D normalized histogram of ridge orientations Pose estimation Algo + Improved LSH for MCC	SVM	-
[79]	Fingerprint recognition by euclidean distance	G	Core & bifurcation points	172 400	ST-BIO Card Reader Model: BCR100T V3.0 VeriFinger Sample DB database [23].	Core: ASDF – Average Square Directional Field	Shortest Euclidian distance core & bifurcation points	Overall precision : 85% ST-BIO Card Reader : 95% VeriFinger Sample DB : 75%
[80]	Minutiae Extraction	L	Minutiae features	-	-	Iterative, parallel thinning algorithm Enhanced thinning algorithm Minutiae Marking: Crossing Number	False Minutia Removal Minutiae Match: alignment-based match algorithm (elastic match algo)	EER: 25
[51]	Texture Feature based Fingerprint Recognition	L	Core	300 fp images	In-house (256*256) FVC 2000	Feature extraction: DWT Core point:	Matching: Euclidian distance	98.98% boost EER: 2.80%

						PoinCare Index		
[81]	Pattern Recognition System	L	Minutiae	900 fp images (each has 500dpi 256 gray level) 269 fingers 450 imgTrain 450 imgTest	IBM HURSLEY database	Learning Vector Quantizer (LVQ)	Feature refinement rule-based classifier LVQ based classifier	95% training 87% testing
[62]	Convolution Neural Networks (CNNs)	G	Singular points	-	FVC 2002 DB (core 2738 Delta 731)	CNN	Two-layer nonlinear CNN classifier	False detection rate: Core 7.5% Delta 6%
[31]	Deep CNN (train minutiae) + K-NN based triplet selection(select proper triplet)	G	Minutiae + Global Pattern	-	In-house DB PHF300 FVC2000 FVC2006	Deep CNN	-	-

FDR: False Detection Rate, CNN: Convolution Neural Network, MCC: Minutiae Cylinder Code, PR: Precision Rate, ASDF: Average Square Directional Field, SVM: Support Vector Machine, LSH: Locality Sensitive Hashing, EER: Equal Error Rate, A-KAZE: Accelerated KAZE, L: Local, G: Global

III. CONCLUSION AND DISCUSSION

This paper presented a review of state of the art methods of fingerprint recognition system. The paper starts with the introduction of biometric technologies which are widely used in forensic applications like criminal investigations, terrorist identification and other security issues in applications such as defence, civilian, commercial era. Fingerprint applications and its history is briefly discussed which is followed by the features of fingerprint. The structure of a conventional fingerprint recognition system is shown which includes various modules. Fingerprint pre-processing techniques such as enhancement techniques, segmentation, binarization, morphological operations etc. used to improve the quality of fingerprint images before further stages of extraction and matching are discussed. Various minutiae and non-minutiae based features extraction techniques are analysed. Combination of these techniques along with advantages and limitations are specified. Template matching and machine learning techniques are presented with a brief discussion.

It is observed that, non-minutiae features are not sufficient for matching purpose because of their distinctiveness. Also according to survey, minutiae points solely do not provide satisfying accuracy and results as these points does not give any details about surrounding pattern whether it is ending or bifurcation. Thus extracting local structure of these minutiae points provides better results.

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