Review and Evaluation of Fingerprint Singular Point Detection Algorithms

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Review and Evaluation of Fingerprint Singular Point Detection Algorithms

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Authors' contributions

Author GBI conducted and wrote the review of fingerprint singular point detection algorithms and the synopsis of the existing singular point detection works. He also carried out the experimental evaluations. The Introduction and the Conclusion drawn from the study were jointly formulated by the authors while author SOO severally proof read the manuscript to ensure its high quality and good technical standards.

Article Information

| Review Article |

ABSTRACT

Fingerprint has continued to enjoy dominance over other biometrics like face, iris, nose, signature among others in human verification and authentication. This is promoted by its major characteristics which include availability, uniqueness, consistency and reliability. Fingerprint verification and authentication involves the serial stages of enrolment, processing and matching. Enrolment through a number of fingerprint capturing devices helps to read the fingerprint into a target location from where processing takes place. Processing of a fingerprint image involves enhancement, feature extraction and singular point detection. Matching of fingerprint is performed based on the extraction results to

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establish its source or similarity level. The extraction of true singular (core and delta) and feature points is paramount for a true fingerprint matching and a number of algorithms had been formulated to accomplish it. This paper presents a review and evaluation of commonly known fingerprint singular point detection algorithms with emphasis on methodologies, strengths and weaknesses.

Keywords: Fingerprint; singular point; core and delta; Poincare; orientation field; geometry of region.

1. INTRODUCTION

Fingerprints are the results of minute ridges and valleys found on the thumb of every person. It is an impression of the friction ridges of all or any part of the thumb. Fingerprint is also an impression of the coetaneous ridges of the fleshy distal portion of a thumb, which may be made by applying ink and pressing the thumb on paper [1-2]. Among all the biometric indicators, fingerprint maintains one of the highest levels of reliability, consistency and uniqueness and is extensively used for identifying individuals [4-5]. During fingerprint matching both the coarse and smooth level characteristics are used. At the coarse level, fingerprints are classified into six main classes which are arch, tented arch, right loop, left loop, whorl and twin loop which are shown in Fig. 1 [1-2,5-9].

| Twin Loop | Left Loop | Right Loop | Whorl | Arch | Tented Arch |
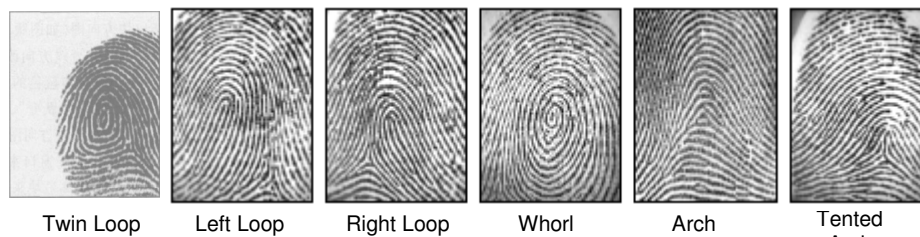
Fig. 1. Fingerprint ridge patterns

Smooth-level fingerprint matching is performed by comparing the ridge ending, bifurcation and the singular points extracted from fingerprint images. As shown in Fig. 2, the ridge ending is any point at which the ridge terminates while the ridge splits into two at a bifurcation point. The singular point is defined as the point where the ridge curvature is higher than normal and where the direction of the ridge changes rapidly. It can also be viewed as points where the orientation field is discontinuous. Singular points can be classified into two types; namely core and delta which are shown in Fig. 3 [10].

At the core point, the pattern exhibits the semi-circular tendency whereas the patterns split into three different sectors at the delta point, and each sector exhibits the hyperbolic tendency [11,12]. Singular points are used for fingerprint indexing, classification, arrangement and orientation field modelling [12-15]. They are also used in fingerprint matching [13,16].
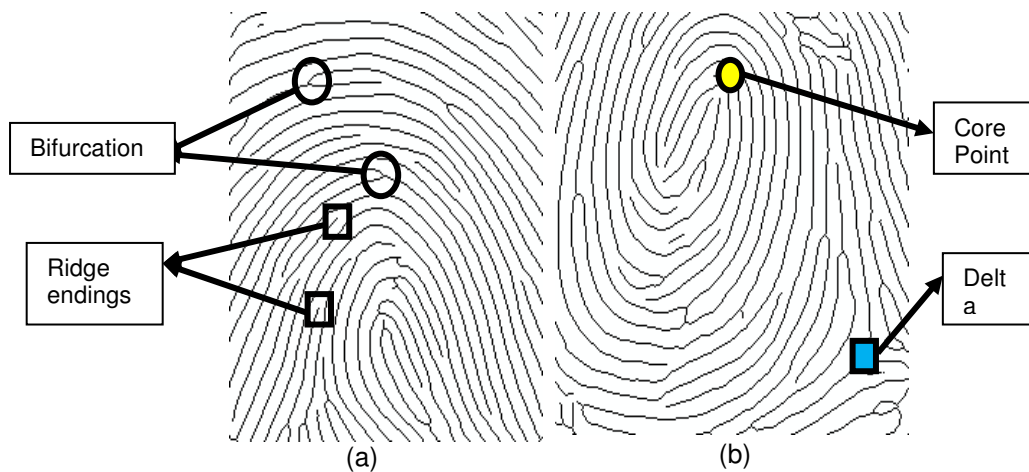
Fig. 2a. Fingerprint showing the bifurcation and ridge ending. (b) Fingerprint showing the core and delta points

A number of fingerprint feature extraction algorithms have been formulated with their attendant strength and weaknesses. They include Crossing Number [17-21], Adaptive Flow Orientation [22], Orientation Maps [23], Gabor Filter [14]. Others are Mathematical Morphology [24], Minutiae Maps and Orientation Collinearity [25] and Adaptive Flow Orientation [22]. The Crossing number algorithm suffers the extraction of false minutiae in cases of distorted images, the Mathematical Morphology Approach is susceptible to missed minutiae while the Adaptive Flow Orientation algorithm experiences a considerably high operational time. The existing fingerprint singular point detection algorithm include Poincare Index [11,26-28]] Curvature [29], Multi-Resolution [16], Orientation Field [30-33]. In some cases, the existing techniques for the detection of the singular points do not produce expected or accurate results, especially for noisy images [4,10,34]. Some of them are selective in the nature of performances, others failed with some patterns of fingerprint [3,5] and some result in many forged detection points due to [10,35]:

a. Insufficiency of the algorithm for accurate singular point detection
b. The use of only local characteristic of singular points by most post-processing approaches, which is not enough to discriminate true singular points from forged detections caused by creases, scars, blurs, damped prints and so on.

Singular points detection methods may also suffer from cropping of the Region of Interest (ROI) thereby containing less information [36]. This paper focused on the survey of some of the existing fingerprint singular detection algorithms focusing on their methods, strengths and weaknesses. Section 2 discusses commonly known fingerprint singular point detection methods while a summary of existing works on fingerprint singular point detection is presented in Section 3. Sections 4 and 5 present the experimental evaluation of the reviewed techniques and the conclusion drawn respectively.

2. FINGERPRINT SINGULAR POINT DETECTION ALGORITHMS

In most cases, the process of the extraction of singular points from a fingerprint image takes the order shown in Fig. 3.
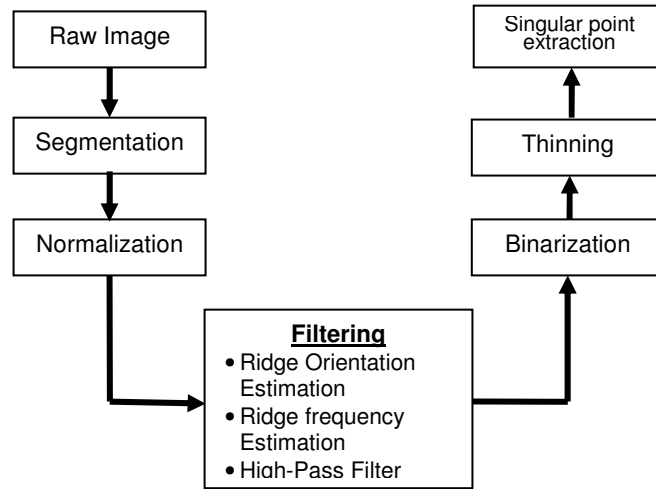
**Fig. 3. Procedure for fingerprint singular point
detection**

The serial process from segmentation to thinning takes care of the image enhancement using a number of algorithms [17,19,37]. For efficient and smooth fingerprint image filtering, three successive operations; namely ridge orientation estimation, ridge frequency estimation and High-Pass filtering are performed. Ridge binarization and thinning are subsequently performed on the filtered image. Some commonly known techniques for the extraction of fingerprint singular points from a thinned fingerprint image are discussed in the following sub-sections.

2.1 Poincare Index Technique

The Poincare Index technique is commonly used for the detection of fingerprint core and delta points [5,12]. In a fingerprint orientation field, the PI of a core-shaped singular region is 0.5 while that of a delta-shaped singular region is -0.5. For pixel P(i, j), its PI is obtained from [5,10,12,27,38-40]:

$$PC(i,j) = \frac{1}{2\pi} \sum_{k=0}^{N_P-1} \Delta(k) \tag{1}$$

$$\Delta(k) = \begin{cases} \delta(k), & if\, \delta(k) < \dfrac{\pi}{2} \\ \pi + \delta(k), & if\ \delta(k) \le -\dfrac{\pi}{2} \\ \pi - \delta(k), & otherwise \end{cases} \tag{2}$$

$$\delta(k) = O'\left(P_x(k'), P_y(k')\right) - O'(P_x(k), P_y(k)), k' = (k+1)mod\ N_P$$

$P_x(k)$ and $P_y(k)$ are the x and y coordinates of the kth point on the closed curve centered at the given point (i, j) and composed of N_P pixels, O' denotes a fingerprint orientation field. To capture the sudden change of orientation, and extract singular points more reliably, the

method is improved by modulating the third part of Equation (2) to $\delta(k) - \pi$ which results in [27]:

$$\Delta(k) = \begin{cases} \delta(k), & if\ \delta(k) < \dfrac{\pi}{2} \\ \pi + \delta(k), & if\ \delta(k) \le -\dfrac{\pi}{2} \\ \delta(k) - \pi, & otherwise \end{cases} \qquad (3)$$

Post-processing steps are often used to resolve associated anomalies in the following ways:

a. Both delta and core are eradicated if the distance between them is smaller than 8 pixels
b. In a circular region with a radius of 8 pixels, if there is more than one core (or delta), an average core (or delta) is calculated instead.

Given that *N* cores (or deltas) exist in an area, {(u_i, v_i), i=1, 2, 3, . . . , N) then, the average core (or delta) (*u*, *v*) is calculated from:

$$u = \frac{1}{N} \sum_{i=1}^{N} u_i \qquad (4)$$

$$V = \frac{1}{N} \sum_{i=1}^{N} v_i \qquad (5)$$

2.2 Orientation Field Technique

Core point orientation indicates the amount of fingerprint rotation that is necessary for aligning two fingerprint images during matching. An iterative method based on the orientation differences between two equal regions defined by the core point geometry is presented below [4,38-39,41-42]:

a. Divide into two equal halves, a semi-circular region of radius *R* below the core point along the dotted line segment. Given that β_{L1} and β_{R1} are the left and right part of the orientation values, then the semi-circular region's orientation $\emptyset_1$ is given by:

$$\emptyset_1 = \begin{cases} 0.5(\beta_{L1} + \beta_{R1}) + 180; & if\ 0.5(\beta_{L1} + \beta_{R1}) < 0 \\ 0.5(\beta_{L1} + \beta_{R1}); & otherwise \end{cases} \qquad (6)$$

$$\beta_{L1} = \begin{cases} \beta_{L1} - 180; & if\ \beta_{L1} > 90 \\ \beta_{L1}; & otherwise \end{cases} \qquad (7)$$

$$\beta_{R1} = \begin{cases} \beta_{R1} - 180; & if\ \beta_{R1} > 90 \\ \beta_{R1}; & otherwise \end{cases} \qquad (8)$$

b. The semi-circular region about the core point $\emptyset_1$ degrees is rotated to produce two equal regions whose dominant orientations are β_{L2} and β_{R2} which are computed using Eq. (8) with β_{L2} and β_{R2} is $\emptyset_2$.

c. The semi-circular region is rotated by $\emptyset_2$ degrees and its orientation $\emptyset_3$ is computed. This step is repeated for a given number of times, with the resulting orientation defined as the core orientation.

The authors in [43-44] used the squared gradient vectors in the neighborhood of a SP for the analysis of the image. The reference model for a core at (a, b)) = (0, 0) is defined by:

$$C_R = \frac{(a-b)}{\sqrt{a^2+b^2}} \tag{9}$$

The model of a core rotated over an angle ρ is given by a reference model with all its components multiplied by $e^{j\rho}$. The orientation of the core, with respect to the reference model, is derived from the inner product of the estimated squared gradient data and the complex conjugated reference model is divided by the number matrix elements N, and the angle is taken as:

$$\hat{\rho} = \frac{1}{S} \tag{10}$$

$$\hat{\rho} =\because \frac{1}{S} \sum_{a,b} C_R^*(a,b) C_{Obs}(a,b) \tag{11}$$

The operator $\because$ provides an accurate estimate for the orientation ρ. If the observed core is exactly a rotated version of the reference core, this estimate gives:

$$\hat{\rho} =\because \frac{1}{S} \sum_{a,b} C_R^*(a,b) C_R(a,b). e^{j\rho} \tag{12}$$

$$\hat{\rho} =\because \frac{1}{S} \sum_{a,b} |C_R(a,b)|^2. e^{j\rho} \tag{13}$$

$$\hat{\rho} =\because e^{j\rho} = \rho \tag{14}$$

2.3 Multi-resolution Directional Field Technique

Core detection algorithm that uses multi-resolution direction field involves the following [45,46]:

a. Compute the directional field O using 64 x 64 block size with 2 x 2 window
b. Compute the gradient of the directional field $O_r(r,s), \ O_s(r,s), O_{rr}(r,s) \ and \ O_{ss}(r,s)$
c. Compute $O_r^2(r,s), O_s^2(r,s), O_{rr}^2(r,s), and \ O_{ss}^2(r,s)$,
d. Compute P(r, s) from:

$$P(r,s) = P(\tau,r,s) \otimes \sigma_o(r,s) \tag{15}$$

$$P(\tau, r, s) = \frac{1}{2\pi\tau^2} e^{(r^2+s^2)/2\tau^2} \tag{16}$$

$$\sigma_o(r, s) = \frac{O_r^2 \, O_{ss}^2 + O_s^2 \, O_{rr}^2}{(O_r^2 + O_s^2)^2} \tag{17}$$

    e.   The core point measure is computed as follows

$$O_r^2 \, O_{ss}^2 + O_s^2 \, O_{rr}^2 = k(r, s) * (O_r^2 + O_s^2)^2 \tag{18}$$

The maximum of σ is taken as the core point.

2.4 Gaussian Process Prediction Technique

In order to predict the core point, a Gaussian process model with squared exponential covariance function is applied as follows [47]:

    a.   The regression model with Gaussian noise is obtained from:

$$y = f(g) + c \tag{19}$$

f(g) is the value of the process or function *f(x)* at g and *c* is a random noise variable whose value is chosen independently for each observation.

    b.   The noise processes that have a Gaussian distribution is considered and the Gaussian likelihood for core point is given by:

$$p\big(y\big|f(g)\big) = N(f, \partial^2 I) \tag{20}$$

∂^2 is the variance of the noise.

    c.   The Gaussian process is given by a Gaussian whose mean is zero and covariance is defined by a function $k(g, g')$ such that:

$$f(g) \sim \mathcal{GP}\left(0, k(g, g')\right) \tag{21}$$

    d.   The squared exponential covariance function is used to specify the covariance between pairs of variables, represented by θ_1 and θ_2:

$$k(g, g') = \theta_1 e^{(-\frac{\theta_2}{2}|g-g'|^2)} \tag{22}$$

The optimization of the hyper parameters θ_1 and θ_2 are obtained by maximizing the log of the likelihood $p(\mathbf{y}|\theta_1, \theta_2)$.

    e.   Given that the input orientation map of a fingerprint is given by $\mathbf{g}*$, the Gaussian predictive distribution of the core point $y*$ *is* evaluated by conditioning the joint Gaussian prior distribution on the observation $(G, \mathbf{y})$, where $G = (\mathbf{g}_1, \ldots, \mathbf{g}_N)^\mathsf{T}$ and $\mathbf{y} = (y_1, \ldots, y_N)^\mathsf{T}$. The predictive distribution is obtained from:

$$p(y^*|g^*, G, y) = N\big(m(y^*), cov(y^*)\big) \tag{23}$$

$$m(y^*) = k(g^*, G)[K + \partial^2 I]^{-1}y \tag{24}$$

$$cov(y^*) = k(g^*, g^*) + \partial^2 - k(g^*, G)^T[K + \partial^2 I]^{-1}k(G, g^*) \tag{25}$$

K is the Gram matrix whose elements are given by $k(\mathbf{g}_i, \mathbf{g}_j)$.

    f.   The core point of fingerprint is given by:

$$\widehat{y^*} = k(g^*_{MAX}, G)[K + \partial^2 I]^{-1}y \tag{26}$$

g^*_{MAX} is the orientation map.

    g.   The maximum predictive probability of core point is obtained from:

$$g^*_{MAX} = argmax \; p(m(y^*)|g^*, G, y) \tag{27}$$

The core point prediction and subsequent latent print localization given three different latent fingerprints presented in [47] are shown in Fig. 4. The latent fingerprints were obtained from the NIST 27 [48] which contains latent fingerprints from crime scenes with their matching complete fingerprint mates. Images on the left side represent the photographs taken from crime scenes with the latent fingerprints obtained from the areas enclosed in rectangles. The fingerprints on the right side show the orientation maps of latent prints and their positions in complete mates. The crosses denote the true core points detected in the corresponding complete fingerprints. The core points predicted by Gaussian processes are presented by the rounds. This method can correctly predict the position and direction of the core points if the latent fingerprints contain sufficient features such as ridges Fig. 4(a) and Fig. 4(b). This method fails with too small latent fingerprint or insufficiently discriminative features (Fig. 4(c)).

2.5 Geometry of Region (GR) Technique

The GR technique is summarized as follows [35, 49]:

    a.   Compute the smoothed orientation field $\theta'(i, j)$.
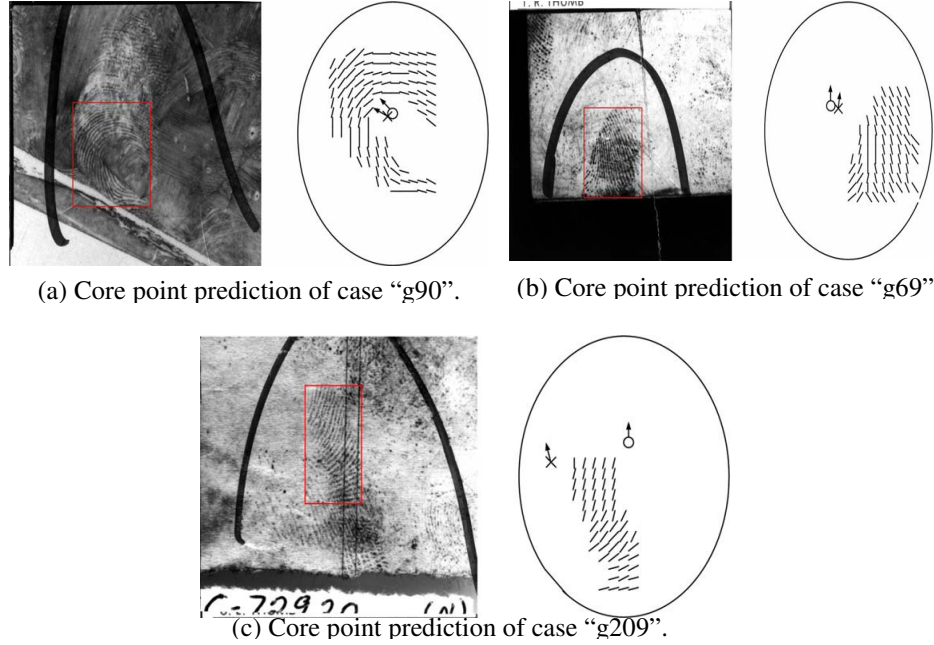   b.   Compute the sine component, $\varepsilon (i, j)$ of $\theta'(i, j)$ by using:

$$\varepsilon(i, j) = \sin(\theta'(i, j)) \tag{28}$$

    c.   Initialize a labelled image A with O indicating the core point.
    d.   Assign the corresponding pixel in A the value of the difference in integrated pixel intensity of each region as follows:

$$A(i, j) = \sum_{R1} \varepsilon(i, j) - \sum_{R2} \varepsilon(i, j) \tag{29}$$

Candidates regions *R1* and *R2* will be determined empirically and their geometry designed to capture the maximum curvature in concave ridges. In practice, the region should cover at least 1 ridge. In addition R1 that sandwiched R2 is expected to hold the maximum point.

e. Find the maximum value in A and assign its coordinate as the core point.
f. If the core point still cannot be located, the steps (a-e) are iterated for a number of times while decreasing the window size.

(a) Core point prediction of case "g90".   (b) Core point prediction of case "g69".


(c) Core point prediction of case "g209".

Fig. 4. Results of Gaussian Process Prediction Technique-based core point prediction and subsequent latent print localization

2.6 Direction of Curvature (DC) Technique

If the tangential angle φ is measured counter-clockwise from the x-axis to the unit tangent $T = \alpha'(s)$, as shown in Fig. 5, then the curvature k of α is the rate of change of direction at that point of the tangent line with respect to arc length and it is obtained from:

.

$$k = \frac{d\varphi}{ds}$$
(30)
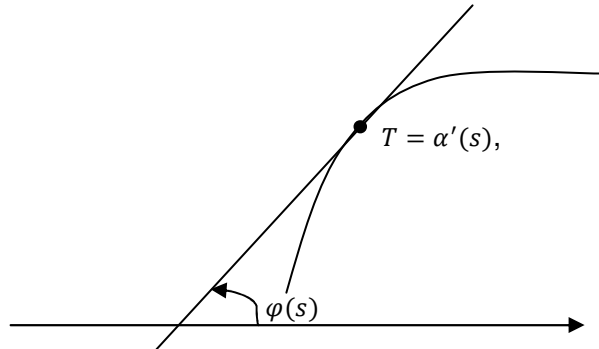
Fig. 5. Tangential angle of a point

Base on this definition, the DC technique for fingerprint core point detection goes thus [35]:

a. Compute the local orientation θ*(i, j)*.
b. Smooth the orientation field θ'*(i, j)*
c. In every progressive block of size w, the difference of direction components is computed as follows:

$$Diff\ Y = \sum_{k=1}^{w} \sin 2\theta\ (k,w) - \sum_{k=1}^{w} \sin 2\theta\ (k,1) \tag{31}$$

$$Diff\ X = \sum_{l=1}^{w} \cos 2\theta\ (w,l) - \sum_{l=1}^{w} \cos 2\theta\ (1,l) \tag{32}$$

d. The curvature point (X) is located at the corresponding *(i, j)* where *Diff X* and *Diff Y* are negative.
e. If the core point of target location cannot be determined, the image size is reduced and core point detection is performed again.

2.7 Complex Filter Technique

This method locates the symmetric parts in the complex orientation field through the application of two types of complex filters for core and delta points. The complex orientation field image is obtained from the input image by using the equation [30,40]:

$$z(x,y) = (f_x + if_y)^2 \tag{33}$$

i is the imaginary unit and $f_x + f_y$ are the derivatives of the input image in the x- and y-directions, respectively . The complex filters for core points (f_c) and delta points (f_d) are derived from:

$$f_c = (x + iy)^m g(x,y) \tag{34}$$

$$f_d = (x - iy)^m g(x,y) \tag{35}$$

Where m is the filter order and g is the Gaussian such that:

$$g(x,y) = exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) \tag{36}$$

Where σ is the variance. The convolution of the complex orientation field image with each complex filter is computed, and then a point with high filter response is considered as a singular point corresponding to the filter type as shown in Fig. 6. In this method, the computation of the convolution takes an $O(n^2 \log n)$ time for the size n^2 of the input image, and the other process are constant or linear to n^2. Therefore the time complexity of the method is $O(n^2 \log n)$.
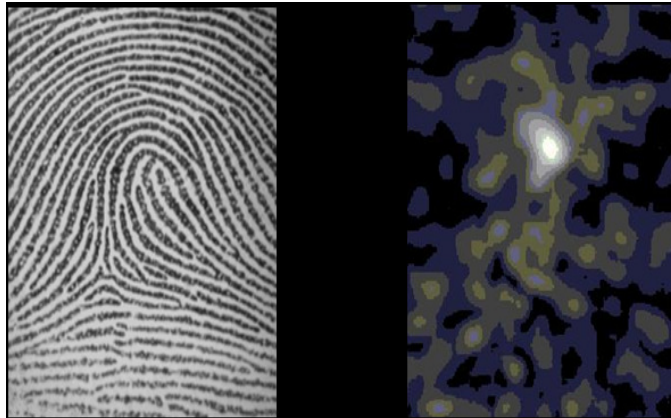
Fig. 6. An input image (a) and the absolute result of the convolution with the complex filter for core points (b)

3. SYNOPSIS OF THE EXISTING SINGULAR POINT DETECTION WORKS

A number of algorithms have been proposed for the optimal detection of the singular points in fingerprint images. The authors in [50-51] presented a technique for the reliable estimation of the orientation field and high percentage detection of the core point in a fingerprint image. The authors in [12,52-53] proposed different algorithms for singular point detection based on orientation field reliability. The algorithms perform fingerprint image enhancement and reliably calculated the orientation field before locating the singular points. In [41], a fingerprint singular points extraction algorithm based on orientation and zero-pole properties is proposed. Singular points are located by clustering the results of corner detection before examining the sub-block orientation fields at a number of selected positions on concentric circles centred in the neighbourhood of the candidate singular point. The authors in [54] employed orientation field, localization and type for its singular points detection. The authors in [5] proposed a continuous fingerprint indexing method based on location, direction estimation and correlation of fingerprint singular points. The orientation field of the fingerprint image is firstly divided into blocks for the computation of the PI and blocks with singularities.

An algorithm for singular points detection based on the conventional PI method to remove spurious singular points is presented in [10]. The algorithm uses the optimal combination of singular points to minimize the difference between the original and the model-based orientation field. It also uses a core-delta relation as a global constraint for the final selection of singular points. An algorithm which is based on orientation field estimation, coherence and Poincare Index (PI) methods is used for consistent core point detection in [44]. The algorithm detects high curvature regions with high accuracy as it combines advantages from individual method. A technique for the accurate estimation of a high resolution directional field from fingerprints is presented in [43] while the authors in [27] presented an algorithm that integrates PI and Multi-Resolution Analysis to detect singular points. Conventional PI method is improved on the basis of the Zero-pole Model analysis to detect singular points with different resolutions. The multi-resolution information of the fingerprint pattern is extracted and the image is divided into non-overlapping blocks on the basis of wavelet functions. The multiple resolution directional fields are computed and block position shifting is performed to capture the features of the ridge direction patterns.

The authors in [45] presented an algorithm that is based on Multi-Resolution Direction Field (DF) and used the low resolution DF to find the singular point and high resolution direction field to search its precise position. An algorithm that searches the directional field with the larger direction changes in a fingerprint image to obtain its singular points is proposed in [3]. The algorithm uses a post-processing method to increase accuracy. It also uses the delta direction and singularities to partition similar classes. Direction of curvature (DC) is used in [35] for the determination of fingerprint core point while geometry of region (GR) is used in its tuning. The authors in [55] located the reference point of the fingerprint based on the rotation-invariant location and Filter-bank-based fingerprint matching algorithm. The optimum values for the number of bands (B), the number of sectors per band (k), and the number of Gabor filters to produce the best result were deduced. A fingerprint core and delta point detection algorithm that uses a directional masks to detect the neighborhood of the singular points is also presented in [56].

The authors in [49] presented a model for determining virtual core point based on changes in gradient at the maxima and minima points while a similar method based on Gaussian processes for the prediction of the locations and orientations of core points for latent fingerprints is proposed in [47]. The method also provides prediction in interpretations of probability rather than binary decision. Principal Gabor Basis Function (PGBF)-based approach is used in [57] to extract cores, deltas, and minutiae from fingerprint images. Poincare index was also used to classify cores, deltas, or minutiae points. A technique that estimates the position of all the singular points by processing the global structure of the ridges and extracting a specific set of features is presented in [58]. Computational intelligence classification techniques were used to process the extracted features for the selection of the reference point from the candidate list. Using local ridge orientation and frequency estimation based enhancement, the author in [59] extracted the core area in a fingerprint. The authors in [42] presented a hierarchical analysis orientation consistency-based approach to fingerprint core point detection. The method uses global thresholding and Artificial Neural Network (ANN)-based geometry of region technique over a small search window for reducing chances of falsely locating a core point due to presence of discontinuities like scars or wrinkles. A mask that locates the core point simply from the ridge orientation map is presented in [60]. The algorithm detects the core point at the end of the discontinuous line appearing in the orientation map presented by a gray-scale. By scanning the ridge orientation map, a property is presented as a mathematical proof of the detection. The authors in [38] presented a technique for recognizing a fingerprint based on the properties of the features within 100 x 100 pixels neighbourhood of the core point. Log-polar mapping was used to extract the translation-invariant features derived from the discrete wavelet frame transform and Bayesian likelihood ratio-based fitness function was devised to genetically select the most discriminative log-polar feature subset by disregarding redundant features via support vector machines classification.

4. EXPERIMENTAL EVALUATION

The evaluation of the fingerprint singular point detection algorithms presented in Section 2 was performed using Matlab in an environment characterized by windows 7 Operating System on a Intel (R) 2.50 GHz dual core Pentium IV with 4.0 GByte RAM. Fingerprint images of diverse qualities from FVC2000 fingerprint database (whose summary is presented in Table 1 were used for the evaluation. The truthfulness of the extracted core and delta points based on visual inspections and the extraction times formed the bases of the evaluation. Some of the results obtained from good, average and bad quality images in the database are shown in Figs. 7(a) and 7(d), Figs. 7(b) and 7(e) and Figs. 7(c) and 7(f)

respectively. For a good quality image, all the algorithms effectively located the core point (in red colours) delta point (in blue colours) with very high degree of closeness and accuracy. Figs. 7(a) and 7(d) present the results for the Poincare, Orientation Filed and Direction of Curvature techniques. With average quality images Figs. 7(b) and 7(e), the algorithms were faced with extraction of few false core or delta points. The highly increased numbers of extracted false core and delta points for very poor quality images by the algorithms are shown in Figs. 7(c) and 7(f). The results presented in Fig. 7 clearly show that the performance of the algorithms is significantly dependent on the quality of the image. Accurate and true detections are attained if the image is of high quality while inaccurate and false detections are recorded for highly degraded images.

Table 1. Details of the standard FVC2000 fingerprint databases

Database	Sensor type	Image size	Number	Resolution
DB1	Optical Sensor	300 x 300	100 × 8	500 dpi
DB2	Capacitive Sensor	256 x 354	100 × 8	500 dpi
DB3	Optical Sensor	448 x 478	100 × 8	500 dpi
DB4	SFinGe v2.0	240 x 320	100 × 8	About 500 dpi

(a)   (b)   (c)

(d)   (e)   (f)
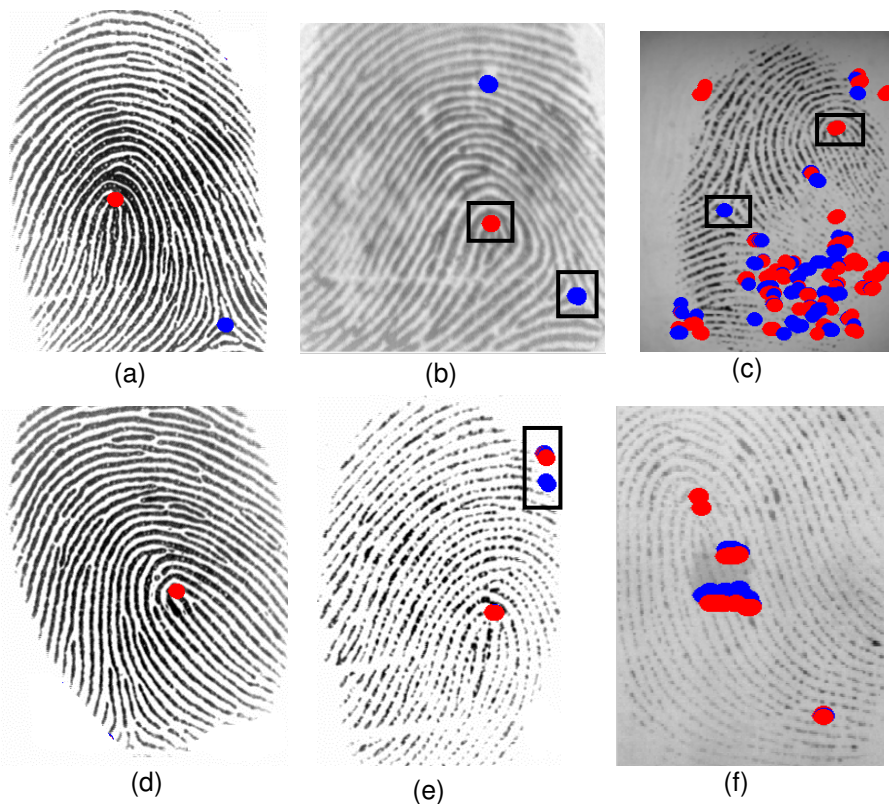
Fig. 7. Obtained singular points detection for images of different qualities

The average times for the Poincare Index (P), Orientation Field (OF), Multi-Resolution Directional Field (MRDF), Geometry of Region (GR) and Direction of Curvature (DC) algorithms to extract singular points from the fingerprints in the four datasets of FVC2000

fingerprint database are presented in Fig. 8. Visual inspection of the fingerprint images in the four datasets shows that the quality level goes in the order of DB2, DB1, DB4 and DB3. This implies that DB2 contains images with the best quality ridge and valley structures while DB3 contains fingerprints with the least quality. In good quality images, the algorithm are saved from the huddle of extracting fictitious singular points resulting in minimal computations while the possibility of false extraction and several computations increases as the quality of the images decreases. This accounts for the lowest and highest extraction times figures recorded for fingerprint images in DB2 and DB3 respectively.

Based on these results, it can be deduced that there is no preferable fingerprint singular point detection method [58]. Most of them give good results for one or two core points but there is virtually none which computes all the cores and deltas [12]. A number of the algorithms such as direction of curvature and directional field cannot justify whether the singularities exists in some position directly, especially with poor quality image, and complex post processing algorithms needed to be used before getting the final results [43,45,49,47,54]. The Poincare Index is only the sum $\Delta(k)$ and contains no information about the arrangement of k. It fails for Arch type of image [4, 51] and it cannot explain the singular point fully and when there are creases, scars, smudges, or damped prints in the fingerprint images, it easily results in many forged singular points even after post-processing as shown in Fig. 9.
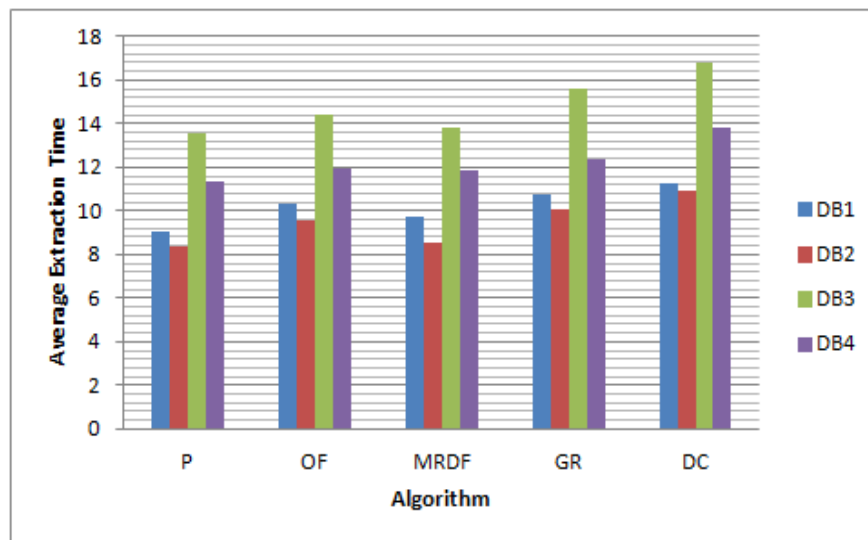
Fig. 8. Average singular Point detection time (sec) for the algorithms on FVC2000 fingerprint database

The forged points greatly degrade the performance of the algorithms [10,41]. The classical formula for computing the Poincare Index presents only the rotation angles, but not the exact direction of the vector in the vector field [5]. Although the Poincare index provides means for consistent detection of SPs, question often arises on its efficient calculation as well as the cumulative orientation changes over contours and their optimal size and shape [43,54]. The summary of the existing works is further presented in Table 2.
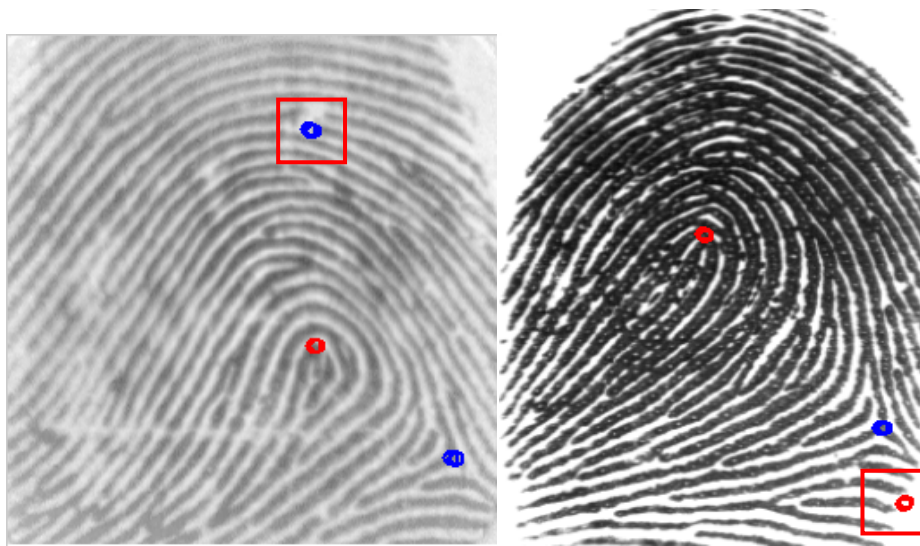
**Fig. 9. Forged singular points detected using a conventional
Poincare Index-based method and post-processing steps, in
which the false points are marked with squares**

Several of the singular points detection algorithms use various techniques that critically rely on orientation fields of fingerprint images. However, orientation field computation itself is a tough task, especially when dealing with poor quality fingerprint images. Furthermore, the choice of block-wised or pixel-wised orientation field is a difficult trade-off as well. Though, block-wised direction has strong capability to avoid spurious detections, there is lower precision in the location of singular points. Relatively smaller block direction can locate singular point more precisely, but cannot effectively counteract the noises impairments resulting in spurious detection [27]. With the orientation field method, singular points are often misjudged especially when dealing with low quality image coupled with a high computational complexity [5]. The technique presented in [12,47,61] gives very good technique for detection of most cores and deltas in a fingerprint image. The techniques also work for all the orientation estimation techniques with almost same results for both good and low quality images. The traditional Poincare index is ameliorated to make it more robust and suitable for multi-resolution orientation fields in [27]. The relationship of singularities detected in different resolution orientation fields and ridges coherence information of candidate singularities are used to properly erase noise-induced singular points. The algorithms presented in [3,5,35,41,51,61] operate at a fast running speed since it only detect the singularities in the effective region of an image. In [10], a Difference of the Orientation Values Along a Circle (DORIVAC) technique is provided in addition to the Poincare´ Index to remove forged detections and to take the topological relations of singular points as a global restriction for fingerprints.

Table 2. Summary of some existing works on fingerprint singular point detection

Research	Methodology	Strength	Weakness
Zhang and Wang [45]	Multi-resolution directional field	Higher precision and robust to noise	Computationally expensive
Anwar et al. [12]	Modified poincare index	Detect all the cores and deltas in an image	The operational speed is low due to un-optimized procedures.
Fei et al. [41]	Orientation field and zero pole models	Consistently extract singular points with high accuracy and speed	Fails in fingerprint with inconsistent orientation field
Basak et al. [49]	Gradient changes	Detect virtual core points	Result not suitable for fingerprint classification
Khalil et al. [52]	Orientation field/short time fourier transform analysis	Consistent and accurate extraction of singular points	Failed with poor quality image
Sim et al. [55]	Rotation invariant reference point location	Accurate detection of the core point	Dependent on sectors and filter sizes
Mei et al. [54]	Orientation field partitioning	Promotion of accurate extraction of singular points	Uncertainty in cases of poor quality images
Song and Elliot [51]	Orientation and edge-map	Singular points detection with high speed and accuracy	Medium performance in case of arch fingerprint type
Bazen and Gerez, [43]	Directional field	Accurate detection of singular point and orientation	Diminishing performance with low quality images
Kekre and Bharadi [44]	Orientation field based on multiple features	Core point detection with very high accuracy	Only detect core points for loop images
Weng et al. [27]	Multi-resolution and poincare index	Erasure of noise induced singular points	Fail when image has resolution problem
Chang and Sargur [47]	Gaussian process	Core point detection for images with or without virtual core points	Only based on probability measure
Julasayvake and Choomchuay [35]	Region of interest	Accurate core point detection with less computation load	Susceptible to false detection
Kharat and Kodwe [10]	Poincare index and DORIVAC	Removal of forged detections	Computationally expensive
Bo et al. [5]	Poincare index	Extraction of singular points with high accuracy	Susceptible to forged detection

5. CONCLUSION

The review and evaluation of several existing fingerprint singular point detection works had formed the focus of this paper. A detailed documentation of the methods, strengths and

weaknesses of some common fingerprint singular point detection works is presented. The review established that the existing algorithms, though, present strong platforms for singular point detection, still experience a number of problems including forged detection, poor performance with low quality image and specificity to certain fingerprint patterns. The results of the experimental evaluations of the algorithms buttressed the findings from the review and further established that the performances of the existing algorithm strictly rely on the quality of the fingerprint images. Future research therefore aims at developing a technique that integrates some of the existing methods to produce a singular point detection method, which eliminates or reduces these problems.

COMPETING INTERESTS

Authors declare that there are no competing interests.

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