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Optimisation of Point-Set Matching Model for Robust Fingerprint Verification in Changing Weather Conditions

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Authors' contributions

This work was carried out in collaboration among all authors. Author IJU carried out the study and wrote the first draft of the manuscript. Authors BIA and BSA provided the statistical and theoretical framework for the study. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To provide a baseline for the configuration of Automated Fingerprint Verification System (AFVS) in the face of changing weather and environmental conditions in order to ensure performance accuracy.

Study Design: Statistical and theoretical research approaches.

Place and Duration of Study: Department of Computer Science and Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria, between July 2017 and July 2018.

Methodology: Data set were collected in the South-South geopolitical zone of Nigeria. We use 10,000 minutiae points defined by location and orientation features extracted from fingerprint samples obtained at 9 various physical and environmental conditions over 12 months period. These data were used to formulate linear regression models that were used as constraints to the verification objective function derived as constrained linear least squares. The effects of the changing weather and environmental conditions were incorporated into the optimised point-set matching model in order to minimise the total relative error on location and orientation differences between pairs of minutiae. The model was implemented using interior-point convex quadratic programming was implemented in Matlab.

Results: The results obtained from the optimisation function by adjusting the thresholds of the

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effects of weather and environmental conditions to 0.0, 0.0 for location and orientation properties of minutiae, respectively, showed minimal total relative errors on the corresponding pairs of matched minutiae, when compared with using the default threshold values of the selected conditions.

Conclusion: The optimisation of point-set based model could provide a computational basis for accurate fingerprint verification for low and high-security AFVS in unfavourable conditions if they are incorporated into the matching model. However, further validation and evaluation of the model with data sets from regions with similar weather and environmental conditions is needed to further validate its robustness in terms of performance accuracy.

Keywords: Optimisation; point-set matching; fingerprint; variable weather conditions.

1. INTRODUCTION

In fingerprint verification, minutiae-based matching approach is considered more efficient approach in terms of distinctiveness and performance [1,2,3,4]. However, other fingerprint matching approaches such as ridge feature and correlation–based approaches have been studied as discussed by Alonso-Fernandez et al. [5]. Minutiae-based matching of fingerprint is often formalised with the point-set based matching models, although there are minutiae matching approaches without point-set matching are studied [6]. The point-set matching model compares a pair of fingerprint described by a set of minutiae points defined by their locations and orientations [7]. The location is defined as a point in two-dimensional space (x_i, y_i) and its angle of orientation from the origin (θ_i). Therefore, given a pair of fingerprint their i^{th} minutiae attributes denoted by $m_i = (x_i, y_i, \theta_i)$, could be compared. Point-based matching model relies on the assumption of geometric transformation to find a unique point on the query fingerprint image and the corresponding minutiae template that relates to each other. The geometric transformations that are used in point-set matching depending on researchers' choice include affine, rigid, non-linear and topological transformations. These transformations have efficiently address rotating, contracting or expanding effects of the minutiae features.

Despite several researches on fingerprint verification, errors are often recorded in the deployment of this system to fieldwork. For instance, in Nigeria where optical sensors are the preferred choice in most government and private organisations applications, error rates are recorded in fieldwork such as verification of candidates for examination, voters and other identity registration exercises. The system failure arises due to the uncontrolled weather and environmental conditions. This failure rate is often recorded in terms of False Acceptance Rate (FAR) and False Rejection Rate (FRR).

Studies have shown that optical fingerprint sensors when exposed to moisture, sunlight could posed a challenge to accurate capturing of data as well as depletion of the quality of fingerprint image. This often results in the low performance of AFVS. Nevertheless, there are other variable physical and environmental conditions which are yet to be identified and how they affect the verification application. Therefore, in order to improve the performance of the fingerprint matching system in the face of these challenges, an optimised verification model which addresses some variable weather conditions that affect the verification system is formulated. The formulated model is defined as constrained linear least squares problem based on the strength of point-set based matching model to minimise matching errors given these conditions of the weather and environment. The constraints of the model were obtained from the linear regression analysis of 10,000 minutiae points extracted from a fingerprint of individuals given 9 different variable physical and environmental conditions over 12 months period, in the South-South geopolitical zone of Nigeria. The formulated problem is solved using interior-point convex quadratic programming approach.

Also, a recent study in point–based minutiae matching addressed minutiae overlap during fingerprint matching [8]. This problem was addressed by optimal alignment of minutiae via linear least squares. However, matching of noisy samples of fingerprint (e.g. DB3 in FVC2004) performed poorly with this approach. Liu et al., [9] studied a robust point set matching method to find optimum or suboptimal spatial mapping between the two point sets. However, the study assumed the point sets in two-dimensional space as directed and considered only the location feature of point only. This study though relevant to the proposed approach failed to consider point feature as having both the location and orientation features. Uz et al. [10] performed minutiae-based template synthesis and matching but used hierarchical Delaunay triangulation instead of point-set based approach.

In this paper, nine variable weather and environmental conditions in the south-south geopolitical zone of Nigeria only are studied. The optical sensor is the fingerprint data sensing device used in this study. To this end, the paper establishes a baseline for the configuration of AFVS in the face of the effects of changing weather conditions (such as temperature, humidity, sunlight, pressure and dust haze parameters among other conditions) in order to ensure robust performance.

The remaining part of this paper is structured as follows: section 2. presents the review of the related work. Section 3.0, discusses the formulation of the proposed model. Section 4.0, discusses the experiment, result and discussion. Section 5.0 points to the conclusion and future research.

2. LITERATURE REVIEW

A few of the related work is summarised in this section and others are thematically arranged in the accompanying subsections. Zhou et al. [11] proposed a combined local point density and optimisation of pair-wise matching to address large rotation and translation in the geometric transformation of image. This combined approach is defined on image in three-dimensional space and its solution degenerated to minimum weighting of bipartite graph. Also, a graph-based approach was studied using Minutia Tensor Matrix (MTM) for fingerprint matching [12]. This approach is designed to address both local and global matching of fingerprint minutiae based on similarities and compatibilities. Nevertheless, the graph-based solutions to noise and non-linearity problems of fingerprint matching are often time consuming when large minutiae sets are involved. Udo et al. [13] proposed an architecture that considers the improvement on the quality and quantity of fingerprint minutiae instances for accurate verification of fingerprint. This was particularly designed to suit the problem of matching errors resulting from the varying sizes of sensors' areas that are deployed in remote applications. A robust point-set registration using Gaussian mixture models has been proposed by Jiang and Femuri [14]. This study presented a unified framework for the rigid and non-rigid point set registration problem in the presence of significant amounts of noise and outliers. This approach was meant to represent the input point sets using Gaussian mixture models. Thus, the problem of point set registration was reformulated as the problem of aligning two Gaussian mixtures such that a statistical discrepancy measure between the two corresponding mixtures is minimised. Also the algorithm was solved using an iterative closest point method. However, the alignment did not consider the effects of environmental and variable physical conditions on the altered geometry of the minutiae location and orientation information. Nain et al., [15] used the degree of distortion associated with fingerprint minutiae to divide the minutiae into two circular inner and outer regions. The alignment of the minutiae pairs according to the defined regions targeted at addressing the distortion of minutiae. In this approach, the difference between the regions was optimised to minimise the errors between them.

Therefore, this paper incorporates the effects of the changing weather and environmental conditions to the point-set based matching. This is achieved by the formulation of the linear constraints that depicts these conditions on both the location and orientation geometry of the fingerprint minutiae. These constraints are used as preconditions for the overall optimisation of the point-set based matching algorithm.

2.1 AFVS in Changing Weather Conditions

Olsen [16] evaluated the performance of fingerprint matching system that takes the moisture content of skin into account with modern optical sensor. The study revealed that the moisture level in the fingerprint has a direct bearing on the biometric performance. Water resistant sensor surface was recommended for use to avoid compromising the quality of the fingerprint image. This study was performed with one variable weather condition with recommendation of hardware solution approach to ameliorate the challenge. Stewart et al. [17] studied and evaluated the performance of fingerprint matching system in rugged outdoors and cold weather conditions. This study revealed that due to fingerprint physiological issues, temperature and humidity could cause low compliance of friction ridges on the optical sensor. Also, in sunny weather condition, ghost images are also formed as a result of sunlight which passes through the latent fingerprints of previous users of the sensor and also cupping of hands around the optical sensors in situations where the sunlight counters the brightness of sensor indicator. Ghost images are also formed in cold condition due to condensed water collected on the surface of sensors on wet snow winter day. Although, anecdotal evidence has suggested a difference between the false rejection rate and temperature as well as humidity, experiment conducted had no significant correlation. The study concluded that biometric performance has no significant dependence on temperature range between $-30℃ - +20℃$ and humidity. It also affirms that chips on optical fingerprint sensors have challenges in the rugged and cold weather conditions that could be addressed during system design. Clark et al., [18] studied the impact of geography, culture and social conditions on the effective collection of biometrics. The challenges of future deployments were addressed in some selected biometrics traits such as fingerprint and face. The study showed that blowing sand in a dry environment can short circuit the electronic sensing devices by entering the small opening on the device. Also, abrasion may be caused as a result of sand blasting on the surface of fingerprint sensor, thus affecting the quality of the sensed fingerprint image. Dirty environment can also cause the definition of valleys and ridges demarcations to be erroneous, thus affecting accurate features extraction in AFVS. Lastly, Elliot et al., [19] conducted a study on environment, image quality and biometric systems and discovered that they contributed to successful implementation of biometric technology. The study also concluded that challenges posed by these factors could be addressed through improvement in algorithm.

Therefore, based on the literature reviewed, there is the need for robust fingerprint verification system in changing weather conditions. In this paper, a computational approach rather than expensive hardware-based solutions to fingerprint verification in a humid tropical weather and other environmental conditions are addressed. This is with a view to establishing a baseline for the configuration of AFVS in the face of changing weather conditions for higher performance accuracy in the south-south geopolitical zone of Nigeria.

2.2 Instances of Fingerprint Verification Error in Nigeria

Being a highly humid tropical region, south–south geopolitical zone has its peculiarities regarding the effects of weather conditions on certain technology e.g. AFVS. News on failure fingerprint verification systems during major examination and other identity verification exercises are available in both the print and online media. For instance, during the verification of candidates for an annual Unified Tertiary Matriculation Examination (UTME) conducted by Joint Admissions and Matriculation Board (JAMB) in 2018, fingerprint related failures were part of the issues affecting over 12,000 candidates [20]. Similarly, in 2015 during Independent National Electoral Commission (INEC) field testing of fingerprint applications held in the 12 states from 6 geopolitical zones of Nigeria, 41 % failure rate was recorded [21].

2.3 Point-set Based Fingerprint Matching

The point-set matching model compares a pair of fingerprint described by a set of minutiae points (e.g. locations and orientations) correspondences [7]. This is because it is difficult to ascertain accurate correspondences between minutiae pairs of the same fingerprint due to several factors such as sensing induced image errors and effects of physical and environmental conditions which could result in distortion, translation, overlap, rotation, depleted quality of image and malfunctioning of AFVS. Many researches to match minutiae correspondences based on point-set based approaches exist [8, 9, 10, and 22]. Other researches using minutiae points include [6,23]. Basically, point-set based matching assumes the query fingerprint minutia is a geometrically transformed template fingerprint minutia. Therefore, finding distance between the pair could result in match or non-match decisions given a predefined threshold value. In this paper, an affine transformation is used. Other geometric transformations used in fingerprint matching are rigid transformation [9], non-linear and topological transformations.

2.4 Linear Least Squares Method

In linear least squares method, a function is minimised that is a sum of squares. This approach was adopted in fingerprint verification to address minutiae overlap by optimal alignment of minutiae via linear least squares [8]. The alignment based on least squares although it provides an iterative based matcher fails to address any effects of the variable weather and environmental conditions in the model to reduce matching errors. The merit of this approach is that it aligns the minutiae pairs optimally and restricts the matching procedure to maximum one-to-one pairings of minutiae that should not be exceeded.

2.5 Interior-point Convex Quadratic Programming

Interior-point method provides a technique to approach an optimal vertex by moving through the interior of the feasible regions [24, 25]. This approach to solution is used to avoid the curse of dimensionality posed by combinatorial feature of linear programming and it is synonymous with iterative closest point algorithm [26]. The essential steps of generic optimisation algorithm followed by this algorithm are modified to suit the verification algorithm presented in this paper. These steps include arbitrary starting point, search direction, computation of step size and the termination criteria for iteration and objective function tolerance. This is to ensure efficiency and speed in minutiae points matching formulated as constrained linear least squares.

3. METHODOLOGY

3.1 Model Formulation

The fingerprint verification problem is formulated as constrained linear least squares and solved using interior-point convex quadratic programming method. This procedure could be used to create a family of parametised approximate solutions that asymptotically converge to the exact solution [20]. Therefore, the two major components of this model are the objective function and constraints.

3.2 Objective Function

This is obtained by the incorporation of the selected variable physical and environmental conditions into the point-set based matching model. The model compares a pair of fingerprint described by a set of minutiae points (m_i). These points are defined by their positions and orientations coordinates, $m_i = (x_i, y_i, \theta_i)$, where m_i is the i^{th} minutiae and (x_i, y_i) is the minutiae coordinate and θ_i is the orientation angle of minutiae. Point-based matching model relies on the assumption of geometric transformation to find a unique match between the query fingerprint image and the corresponding minutiae template based on certain distance measure (e.g. Euclidean distance). As a sequel to this assumption, global rotation and transformation function is defined for the query minutiae points. In this paper, Affine transformation is used to address the rotating, contracting and expanding effects of the minutiae features. The fingerprint verification problem objective function is formulated in equation 1. Where Z is the result of the objective function obtained over the effect of selected weather and environmental conditions, D is the distance measure obtained from the point-set based model for each pair of minutiae points, w is the effect of the variable physical and environmental condition and d is the minimum value between the query and template minutiae and their absolute deviation from angle at a point for each pair of minutiae.

$$\min_{w} Z = \left||Dw - d|\right|_2^2 \tag{1}$$

The objective function in equation (1) is meant to minimise the squared two-norm of the minutiae location and orientation given the effect of weather and environmental conditions. This is subject to the linear constraints derived from the regression analysis of fingerprint data set. To deal with curse of dimensionality often caused by combinatorial features of linear least squares, equation (1) is expanded to fit into a quadratic programming solution offered by the interior-point linear least squares algorithm. This expansion yields equation 2, which fits into a quadratic programming framework (Kruth, 2008). Where D^T is the transpose of D.

$$\min_w Z = \frac{1}{2} w^T (2D^T D) w + (-2D^T d)^T w \tag{2}$$

3.3 Linear Constraints

10,000 minutiae points defined by location and orientation features (x, y, θ) were extracted from the fingerprint of individuals obtained by also measuring 9 different variable physical and environmental conditions over 12 months period, in the South-South geopolitical zone of Nigeria. These data were used to formulate linear regression models which were used as the constraints to the verification objective function. The summary of coefficients of the selected models based on the two measurable properties of minutiae location and orientation information are presented in equation 3. These coefficients of the effects of weather and environmental conditions considered in this paper are summarised on the left-side and the default values of these effects (i.e. the intercepts obtained through regression analysis of the collected data) are given on the right-side of the equation 3. Where $w_{1,} w_2, w_{3,} w_4, w_5, w_6, w_7, w_8$ and w_9 are ambient temperature (in Celcius), relative humidity of the location measured (as percentage), atmospheric pressure measured (in mmHg), brightness of the sunlight measured (in lux), speed of the wind measured (in m/s), dust haze measured as light absorbance (in lux), number of extracted minutiae per fingerprint and number of weeks over the same fingerprint data was sensed.

$$\begin{bmatrix} -0.047301 & 0.044355 & 0.11878 & 0.0000466 & 0.032127 & 0.10203 & -0.0138450 & -0.0000157 & -0.0047289 \\ 0.52335 & 0.70625 & 0 & -0.0057515 & 0 & 2.7067 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \\ w_7 \\ w_8 \\ w_9 \end{bmatrix}$$

$$\leq \begin{bmatrix} -11.006 \\ 55.284 \end{bmatrix} \qquad (3)$$

3.4 Conditions for Matching of Minutiae

The conditions for the matching of pairs of minutiae and overall acceptance or rejection of the fingerprint verification result are derived from an ideal scenario. In an ideal scenario, the pairs of minutiae obtained from the query fingerprint are the same in location and orientation from the ones stored in the template obtained during registration. In this case the result of the objective function $f(x) = 0$. Therefore, to set a matching threshold for a pair of minutiae to be either accepted as a matched or rejected as a non-matched pair; the range of values $(-0.5 \leq f(x) \leq 0)$ must be satisfied. Secondly, the result of the minutiae pair that satisfies the aforementioned interval must also lead to the point of convergence for the fingerprints to be accepted as a match; otherwise it will be rejected as a non-match. These two conditions are used in the place of computed matching score as it is the case with point-set matching approach. The choice of this approach of minutiae point matching is informed by the interior points within a feasible region that can satisfy the minimal total relative error between the location and orientation of the minutiae pair with minimal effects of environmental and weather conditions.

4. MODEL IMPLEMENTATION

The formulated constrained linear least square model is solved using interior-point convex quadratic programming approach. The optimisation toolbox in Matlab is used. The version of the Matlab used is R2015a. The different parameters used for simulation is tabulated in Table 1. The following inputs are defined in Matlab workspace such as expressed in equations 2 and 3. The details of subsequent procedures for model implementation include: definition of the problem in the optimisation toolbox and running the optimisation. The result of the objective function at iteration is used to determine matched and non-matched minutiae point(s) to the point of convergence. The optimised variable physical conditions and environmental parameters obtained from the implementation were also recorded. The system was validated with test data set obtained with optical sensor in the 12th month of the period of study at different weather conditions. The result of verification of an instance of successful verification of matched points using the formulated model is shown in Table 1. The table consists of the different result of parameters obtained during the verification of two same fingerprints obtained at optimal set threshold value $(T = 0.0,\ 0.0)$ of effects of variable weather

Table 1. Different results obtained during verification of 40 pairs of minutiae extracted from an individual fingerprints at optimal variable weather threshold values, $(\boldsymbol{T = 0.0,\ 0.0})$, of both location and orientation information, respectively.

Iteration	f(x)	Feasibility	First order optimality	Total relative error
0	6.417441e+03	3.931e+00	3.253e+03	1.620e+04
1	1.064988e+01	0.000e+00	1.675e-01	1.982e+01
2	1.393693e+00	0.000e+00	5.722e-02	2.882e+00
3	-1.424294e-01*	0.000e+00	1.594e-02	3.987e-01
4	-4.197758e-01*	0.000e+00	2.228e-03	3.936e-02
5	-4.547036e-01*	0.000e+00	7.312e-05	9.467e-04
6	-4.549965e-01*	0.000e+00	3.656e-05	1.330e-04
7	-4.550256e-01*	0.000e+00	5.398e-06	1.122e-05
8	-4.550264e-01*	0.000e+00	3.878e-08	7.856e-08
9	-4.550264e-01*	0.000e+00	2.350e-14	5.029e-14

**Objective function values that satisfy specified range of matched minutiae.*

Table 2. Different results obtained during verification of 40 pairs of minutiae extracted from an individual fingerprints at default variable weather threshold values,$(T = -11.006,\ 55.284)$, of both location and orientation information, respectively

Iteration	f(x)	Feasibility	First order optimality	Total relative error
0	6.417441e+03	1.124e+01	3.253e+03	2.195e+04
1	1.572742e+03	1.112e+01	1.626e+03	4.854e+03
2	1.290731e+07	0.000e+00	5.352e+02	1.389e+07
3	4.590484e+06	0.000e+00	9.570e+01	2.135e+06
4	2.845048e+06	0.000e+00	1.533e+01	1.066e+05
5	2.744308e+06	0.000e+00	6.218e-03	5.981e+01
6	2.744250e+06	0.000e+00	7.276e-12	1.211e-08

and environmental conditions on the location and orientation features of fingerprint, respectively. On the Table 1, the objective function results from iteration 1 to 9, satisfy the matching threshold values to the point of convergence. Therefore, the fingerprint verification result is accepted as a match. On the contrary, the validation of algorithm with the same data set used to in Table 1, without adjustment on the threshold of the variable weather and environmental conditions recorded a non-match verification result as recorded in Table 2. These results of Table 2 were recorded based on the default threshold values of the effects of the weather and environmental conditions obtained during data analysis.

The comparison of the output of parameter values in the two tables shows different results of the objective function although the same fingerprint minutiae were used for the experiments.

5. RESULTS AND DISCUSSION

The results obtained from the optimisation function by adjusting the thresholds of the effects of weather and environmental conditions to 0.0, 0.0 for location and orientation properties of minutiae, respectively, showed minimal total relative errors on the corresponding pairs of matched minutiae, when compared with using the default threshold values of the selected conditions. This implies that error associated with effects of the weather and environmental conditions on location and orientation alignment of minutiae pairs are reduced by the optimisation. The resulting minimal effects of weather and environmental conditions that resulted in the results on Table 1 were as follows: $w_1 = 0.130$, $w_2 = 0.001$, $w_3 = 0.006$, $w_4 = 0.08$, $w_5 = 0.010$, $w_6 = -0.03$, $w_7 = 0.012$, $w_8 = 0.016$, $w_9 = 0.01$. These values are far less than the corresponding values that resulted in Table 2. This also implies that the default weather and environmental parameters were minimised by the implemented system to achieve accuracy. Also, out of 45 minutiae points extracted and used for fingerprint verification, genuine point matches were determined if at least 3 % of the points meet the matching criteria or converges at feasible region. It was observed that the result recorded by the optimised model using the minimal effects of weather and environmental conditions threshold values (T=0.0, 0.0) was more accurate than when the adjustment of weather parameters were ignored. This shows that user-friendly security applications with fingerprints could be built by taking cognizance of the effects of variable and environmental conditions of the environment.

6. CONCLUSION

The optimisation of point-set based model could provide a computational basis for accurate fingerprint verification for low and high security AFVS in unfavourable weather and environmental conditions. This could be achieved by incorporating the effects of these conditions into the matching model. However, other point-set based approaches that considered minutiae points that are invariant to translation and rotation only could cause matching errors in the face of changing the weather and environmental conditions. This study is limited to the computational approach rather than hardware-based approach to solution to changing weather conditions on AFVS. However, further validation and evaluation of the model is needed to further validate its performance accuracy with data set from selected regions of similar weather and environmental conditions. In future, the study could be extended to other regions. It will also incorporate the effects of occupational hazards that hinder the robust performance of AFVS.

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COMPETING INTERESTS

There is no competing interest as the scientific responsibilities of this paper remains with the authors only.

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