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On Matching Altered Fingerprints

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Abstract

Fingerprint alteration refers to changes made in a person's finger ridge structure by means of abrading, cutting, or performing plastic surgery on the fingertips. Fingerprint alteration is a serious attack on Automated Fingerprint Identification Systems (AFIS) since it can reduce the similarity between fingerprint impressions from the same finger due to the loss of genuine minutiae, increase in spurious minutiae and distortion in spatial distribution of the minutiae. We investigate the capability of a state-of-the-art commercial fingerprint matcher to match altered fingerprints to their pre-altered mates by removing spurious minutiae in the altered region. We also attempt to restore minutiae structure in a well-known type of fingerprint alteration, called 'Z'-cut, which tears local skin patches of a finger and switches them with each other. Nonrigid skin distortion introduced during switching of local patches is modeled by thin-plate spline (TPS). Experimental results show that removing spurious minutiae in the altered region and relocating the minutiae in the restored local patches improve the matching performance and help to retrieve correct mates from a large background fingerprint database.

1. Introduction

For over a century, fingerprint recognition has been successfully used for reliable human identification, primarily in law enforcement and forensic applications. Law enforcement agencies worldwide routinely collect all the ten fingerprints of apprehended criminals; for example, the FBI's Integrated Automated Fingerprint Identification System (IAFIS) currently holds 70 million fingerprint records [1]. The success of automated fingerprint identification technology in law enforcement has led to its adoption in various government and civilian applications such as border control, employment background check, and secure facility access [9]. The Department of Homeland Security operates the US-VISIT system which monitors the U.S. border crossings in an attempt to identify high profile criminals on a watch list and detect possible visa fraud [2].

The widespread deployment of AFIS gives incentive to some individuals, e.g., criminals and illegal aliens, to evade fingerprint identification by altering their fingerprints. The objective of fingerprint alteration, also called fingerprint obfuscation, is to conceal one's identity by abrading, cutting, burning fingers or performing plastic surgery on fingertips [13]. If a person has a prior criminal record, he hopes that his altered fingerprints will not be successfully matched to his reference fingerprints stored in the law enforcement databases.

A number of fingerprint alteration cases have been reported in the popular press; in virtually all of the high profile cases of fingerprint alteration, the alteration was detected only after the individuals had been arrested based on ancillary information such as the person acting suspiciously or carrying false documents. For example, in 2005, a drug dealer named Marc George was apprehended because his limping gait, as a result of transplantation of his friction ridges from sole of the foot to his fingertips, caught the attention of border officials [10, 3]. In 2009, a woman successfully evaded the Japanese immigration AFIS by surgically swapping fingerprints of her left and right hands [5]. She was arrested for faking a marriage license, and only later, fingerprint alteration was revealed by scars on her fingers.

Fingerprint alteration does not always fulfill its intended purpose, namely masking one's identity, for the following reasons. (i) Permanent modification or removal of friction ridge pattern often fails since the ridge details in epidermis layer reappear on the surface of the skin after a few months [7]. (ii) Although the local fingerprint information in the altered region is lost, the true identity can be still established based on ridge details in unaltered area. In 1941, Roscoe Pitts, a habitual criminal, had plastic surgery performed to remove the skin of his fingertips and replace it with skin grafts from his chest [3]. After he was arrested by the police, his true identity was revealed as Robert Philipps by

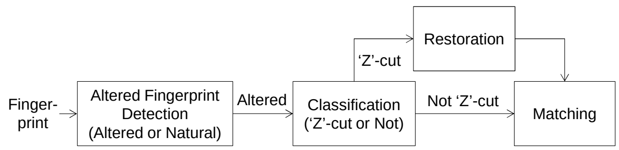


Figure 1. Flow chart for detecting and matching altered fingerprints.

(a) (b)

Figure 2. Examples of obliteration. (a) Scar and (b) mutilation.

(a) (b)

Figure 3. Examples of distortion. (a) Transplantation within a finger by 'Z'-cut and (b) transplantation from other friction ridges.

comparing the second joints of his fingers with the original fingerprint card.

There is also a reported case where altered fingerprints were submitted as a query to AFIS. In 1995, a man named Alexander Guzman was arrested by Florida officials for possessing a false passport. His fingerprints were found to have been altered by a 'Z' shaped cut on the fingertips: two triangular skin patches from the 'Z'-cut were lifted, switched, and then stitched back (see Fig. 3a). Through a manual restoration of his altered fingerprints and a search against the FBI database, the restored fingerprints of Alexander Guzman were linked to the fingerprints of Jose Izquierdo, an absconding drug criminal [12].

With the growing use of AFIS for law enforcement and border control, it is expected that there will be more instances where altered fingerprints will be encountered by the authorities, and AFIS will be expected to find the true identity of the individuals with altered fingerprints. To tackle the problem of fingerprint alteration, new algorithms for detecting and matching altered fingerprints are urgently needed. An overview of the procedure to deal with altered fingerprints is presented in Fig. 1. Fingerprints submitted to AFIS need to pass through an altered fingerprint detector at the front end of the fingerprint matching process. Abnormality in orientation field and minutiae distribution in altered fingerprints provide indication of possible alterations [8, 13]. Once the altered fingerprints are detected, the suspect is sent to a secondary inspection in order to verify (i) that the unusual fingerprint pattern is indeed due to alteration, and (ii) whether these altered fingerprints could still be matched to the suspect's pre-altered fingerprints possibly contained in the databases.

Altered fingerprint matching is a challenging problem due to the following reasons: (i) friction ridge structure can be severely damaged by abrading, cutting, burning, or applying strong chemicals on fingertips, resulting in a number of unreliable minutiae (Fig. 2); (ii) even if the ridge structure is well-defined in local regions, minutiae distribution can be highly unusual during the procedure of switching skin patches in cases of 'Z'-cut prints (Fig. 3a); and (iii) minutiae in well-defined ridge area may not belong to the fingerprint of interest if a portion of skin on the fingertip was transplanted from other parts of the body (e.g., palm or sole) (Fig. 3b).

Matching phase can be divided into two parts: (i) altered fingerprint restoration and (ii) altered fingerprint matching. Among altered fingerprint types, 'Z'-cut cases are of special interest since the original ridge structure of the finger is still retained in the finger, but in different positions. Once the 'Z'-cut prints are detected, the ridge structure in the triangular patches can be restored by reversing the transposing procedure. The restored 'Z'-cut fingerprint and all other altered fingerprints are submitted to a special matcher which is robust to a large amount of skin distortion and utilizes local minutiae information.

In this paper, we investigate feasibility of a state-of-the-art commercial fingerprint matcher to link altered fingerprints to their pre-altered mates by (i) refining the minutiae template that is automatically extracted by the matcher and (ii) restoring altered region in 'Z' shaped cut by swapping two triangular skin patches each other.

2. Matching Altered Fingerprints by AFIS

Fingerprint alteration can severely degrade the matching performance of AFIS due to a decrease in genuine match scores. A commercial state-of-the-art matcher, Neurotechnology VeriFinger SDK 6.3 [4], is used to determine the effect of fingerprint alteration on the matching performance. We also evaluate the following two approaches to improve the matching performance: (i) removing spurious minutiae in the altered region and (ii) restoring minutiae in 'Z'-cut

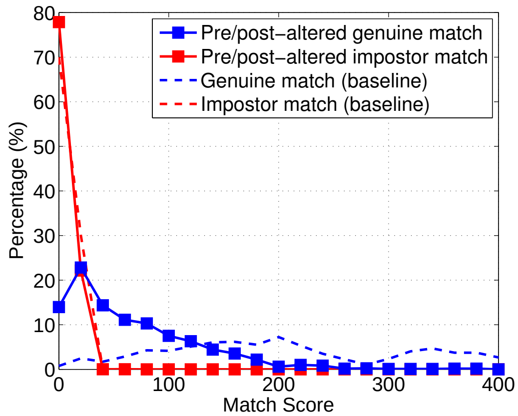


Figure 4. Genuine and impostor match score distributions of altered fingerprint matching and natural fingerprint matching.

skin patches.

2.1. Database

A large database of altered fingerprints is available to us from a law enforcement agency. It contains 4,433 altered fingerprints from 535 tenprint cards of 270 subjects. Among these altered images, 1,332 fingerprints from 382 unique fingers have their pre-altered mates; 'Z'-cut cases are found in 200 fingerprints from 54 unique fingers. If multiple pre-altered impressions of a finger exist, the best quality fingerprint image assessed by NIST Fingerprint Image Quality (NFIQ) software [11] is selected as a reference fingerprint.

2.2. Matching Performance

As a baseline, pre-altered fingerprints from the fingers that have multiple impressions before the alteration is performed are used to evaluate the ordinary matching performance of the given matcher; 287 fingers among 382 fingers which have pre/post-altered fingerprint pairs are found to have multiple pre-altered impressions as well. The number of genuine and impostor matches are 942 and 504,444, respectively. The match score distributions of genuine and impostor pairs in matching between pre-altered fingerprints are shown in Fig. 4, which is considered as typical performance of the matcher. Then, 1,332 pre/post-altered fingerprint pairs are matched. As shown in Fig. 4, genuine score distribution of matching altered fingerprints to their pre-altered mates is significantly shifted towards the impostor score distribution while the impostor score distribution in altered fingerprint matching stays almost the same.

2.3. Spurious Minutiae in Altered Region

Minutiae in the altered region are most likely unreliable since, for instance, scars generate abrupt ridge endings and mutilation forms unusual ridge pattern. In transplanted cases, the ridge structure in the altered region does not belong to the finger of interest. Valid fingerprint region in the altered fingerprint is defined as the unaltered region where genuine friction ridge structure of the finger appears. To establish the valid fingerprint region, region of interest (ROI) of a fingerprint is obtained by measuring dynamic range in local regions, and altered regions also are manually marked. ROI is defined as the local image blocks with dynamic range in gray-scale intensity over 20 after the highest and the lowest 10% gray values in a block are discarded. This is followed by morphological operators to fill holes and remove isolated small regions. With the altered region that is currently marked manually, spurious minutiae in invalid fingerprint region (i.e., either in the altered region or outside ROI) are discarded.

The number of valid minutiae can vary a lot according to the area of valid fingerprint region. The altered fingerprints in Figs. 5a and 5b have very few minutiae that can be useful in matching. In this case, fingerprint matching based on minutiae may not be successful in finding corresponding mates in the database. On the other hand, fingerprints with large valid area contain a number of valid minutiae (see Fig. 5c).

2.4. Restoration of Altered Fingerprints

Minutiae distribution in altered fingerprints is significantly affected by severe skin distortion introduced during the process of alteration. Restoration of altered fingerprints attempts to relocate the minutiae to their original positions by undoing the alteration process, so that skin distortion can be relaxed. However, this is a very challenging problem because (i) each application of 'Z'-cut alteration leads to different outcome in ridge pattern, and (ii) alteration process often discards a portion of the fingerprint.

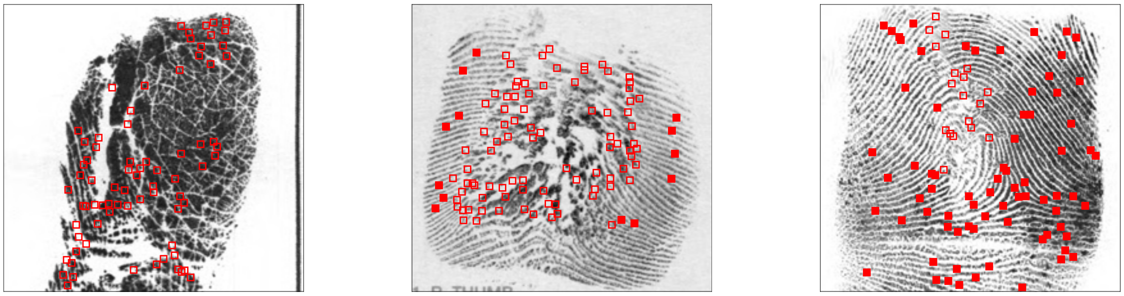
The following procedure is proposed to restore 'Z'-cut fingerprints:

1. Mark edges of each skin patch along the scars and determine a vertex of each patch, $\hat{\mathbf{x}}$ in Fig. 6a, and its new position, $\hat{\mathbf{x}}^*$ in Fig. 6a, to define the rigid transformation of the skin patche (Fig. 7b). One edge of the triangular region is opened and connected to the rest of the fingerprint.

2. Normalize each skin patch to make the boundaries of skin patches flat (Fig. 7c).

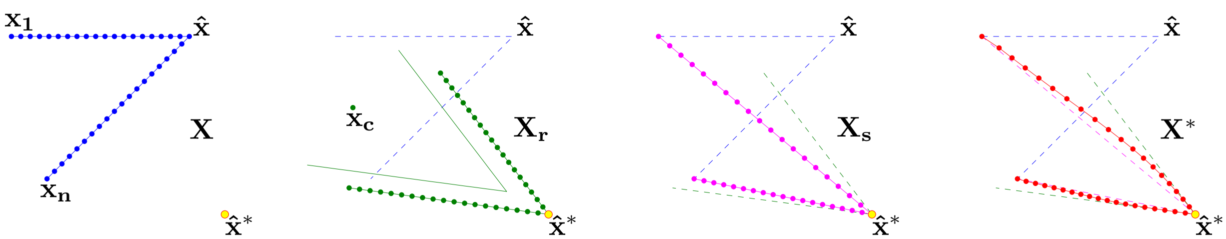
3. Swap the two skin patches based on the thin-plate spline (TPS) model [6] (Fig. 7d).

Normalizing and switching a skin patch follow a nonrigid transformation due to skin elasticity. The skin distortion is modeled by thin-plate spline (TPS) for smooth transition of skin. The boundary of a skin patch is represented by



(a) (b) (c)

Figure 5. Complete minutiae set automatically extracted by the matcher (red squares) and minutiae in valid fingerprint region (red-filled squares). (a) No valid minutiae, (b) very few minutiae in the valid region, and (c) abundant minutiae present in the valid region.



(a) (b) (c) (d)

Figure 6. Transformation of a skin patch in 'Z'-cut fingerprint. (a) Points on a boundary ($\mathbf{X}$) including a vertex ($\hat{\mathbf{x}}$) and a new position of the vertex ($\hat{\mathbf{x}}^*$), (b) rigid transformation of $\mathbf{X}$ ($\mathbf{X_r}$), (c) scaling of $\mathbf{X}$ ($\mathbf{X_s}$), and (d) weighted sum of $\mathbf{X_r}$ and $\mathbf{X_s}$ ($\mathbf{X}^*$).

a set of control points, $\mathbf{X}$; two ending points of the boundary are denoted as $\mathbf{x_1}$ and $\mathbf{x_n}$, and one of the points in $\mathbf{X}$ is selected as a vertex, $\hat{\mathbf{x}}$ (see Fig. 6a). Correspondences in TPS model are built by combining rigid transformation for rotation and translation with nonlinear scaling along two edges while preserving the following constraints: (i) the vertex point, $\hat{\mathbf{x}}$, is mapped to a new vertex position, $\hat{\mathbf{x}}^*$; and (ii) the opened edge to the unaltered region stays in the same position.

The first constraint gives rigid transformation parameters (i.e., rotation matrix $\mathbf{R}$ and translation vector $\mathbf{t}$ in Eq. (1)). For each point $\mathbf{x}$ in $\mathbf{X}$, the rigid transformation is applied as follows:

$$\mathbf{x_r} = \mathbf{R}(\mathbf{x} - \mathbf{x_c}) + \mathbf{x_c} + \mathbf{t}, \tag{1}$$

where $\mathbf{R}$ is the rotation matrix with angle θ,

$$\theta = \arctan\left(\frac{\hat{y}^*}{\hat{x}^*}\right) - \arctan\left(\frac{\hat{y}}{\hat{x}}\right), \tag{2}$$

$\hat{\mathbf{x}} = (\hat{x}, \hat{y})^T$, $\hat{\mathbf{x}}^* = (\hat{x}^*, \hat{y}^*)^T$, $\mathbf{x_c}$ is the center of the rotation defined by the center of two boundary ending points, $\mathbf{x_1}$ and $\mathbf{x_n}$, and $\mathbf{t}$ is the translation parameter to relocate the rotated patch to meet the new vertex, $\mathbf{t} = \hat{\mathbf{x}}^* - \hat{\mathbf{x}}_\mathbf{r}$.

Projection of the control points in $\mathbf{X}$ onto the new edges determined by $\overline{\mathbf{x_1}\hat{\mathbf{x}}^*}$ and $\overline{\mathbf{x_n}\hat{\mathbf{x}}^*}$ gives the scaling factor in smooth transition. For a point $\mathbf{x}$ in $\mathbf{X}$,

$$\mathbf{x_s} = s(\mathbf{x} \cdot \mathbf{e})\mathbf{e}, \tag{3}$$

where s is a scaling parameter defined as the ratio of $\overline{\mathbf{x_1}\hat{\mathbf{x}}}$ to $\overline{\mathbf{x_1}\hat{\mathbf{x}}^*}$ for the control points between $\mathbf{x_1}$ and $\hat{\mathbf{x}}$ or the ratio of $\overline{\mathbf{x_n}\hat{\mathbf{x}}}$ to $\overline{\mathbf{x_n}\hat{\mathbf{x}}^*}$ for the control points between $\mathbf{x_n}$ and $\hat{\mathbf{x}}$, and $\mathbf{e}$ is the unit vector directing from an ending point to the new vertex.

These two transformations are combined by their weighted sum:

$$\mathbf{x}^* = w(|\mathbf{x} - \hat{\mathbf{x}}|)\mathbf{x_r} + (1 - w(|\mathbf{x} - \hat{\mathbf{x}}|))\mathbf{x_s}, \tag{4}$$

where $w(r)$ is a weight function with respect to the distance from the vertex and defined as

$$w(r) = \frac{1}{1 + e^{-ar}}, \tag{5}$$

where parameter a determines the slope of the sigmoid function that adjusts the transition rate between $\mathbf{X_r}$ and $\mathbf{X_s}$ along an edge.

Now, the TPS deformation model is specified by the correspondences between $\mathbf{X}$ and $\mathbf{X}^*$, in addition to the constraint that the open edge of a skin patch stays the same. Fig. 7 shows the restoration procedure of a 'Z'-cut fingerprint and its pre-altered mate for comparison.

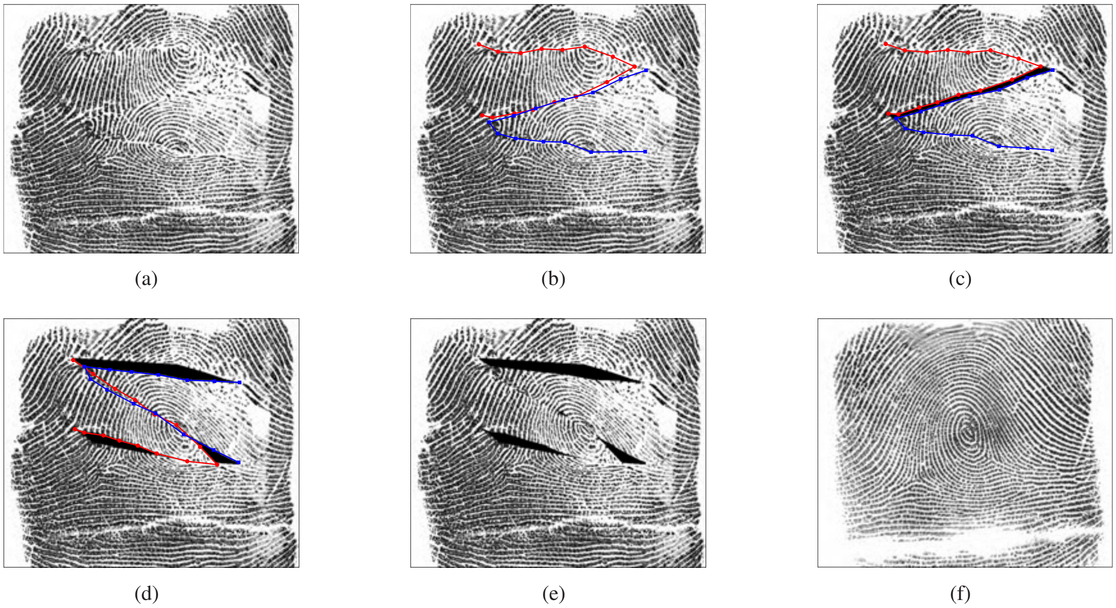


Figure 7. Restoration process. (a) Altered fingerprint image, (b) markups along the edges of each skin patch, (c) normalization of the boundaries, (d) swapping of two skin patches, (e) restored fingerprint, and (f) pre-altered fingerprint of (a).

3. Experimental Results

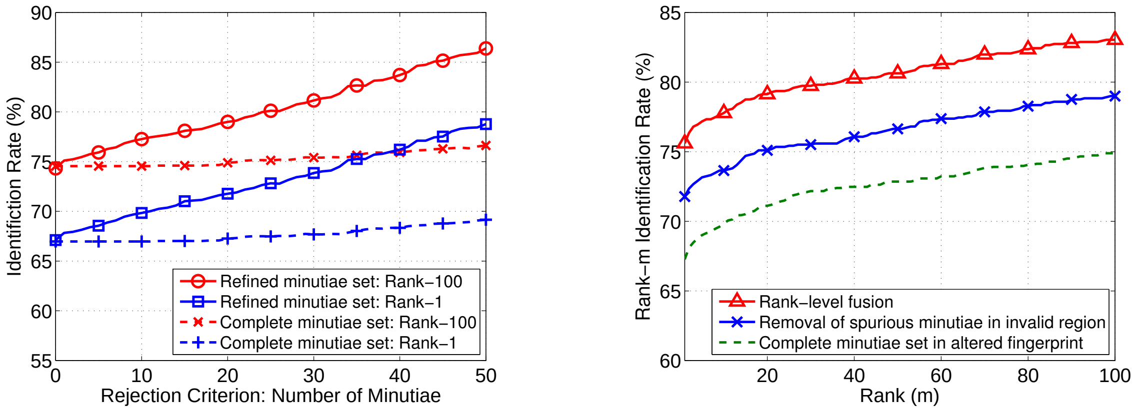
Matching performance of altered fingerprints is evaluated by the Cumulative Match Characteristic (CMC) curves. We view altered fingerprint matching in the same spirit as latent fingerprint matching in the sense that these are high profile cases where a forensic examiner needs to examine top N retrieved candidates from the background database. As a fingerprint matcher, Neurotechnology VeriFinger SDK 6.3 is used to extract minutiae and match the minutiae templates. The altered fingerprint database consists of 1,332 pre/post-altered fingerprint pairs; among them, 200 pairs are of 'Z'-cut type. To enlarge the background database size, 27,000 fingerprints in NIST SD14 were used.

Three minutiae sets are evaluated: (i) all the minutiae extracted from the altered fingerprints, (ii) a subset of minutiae from the altered fingerprints by removing spurious minutiae in invalid fingerprint region, and (iii) a subset of minutiae from the restored fingerprint image by removing spurious minutiae in invalid fingerprint region. Note that all the minutiae in altered fingerprints are automatically extracted by the matcher, and then spurious minutiae in invalid region are masked out.

A query minutiae template is rejected if the total number of minutiae in valid fingerprint region is smaller than a threshold. Fig. 8a shows rank-1 and rank-100 identification rate with respect to the threshold for minutiae template rejection. The minutiae templates refined by removing spurious minutiae in the invalid fingerprint region significantly improve the matching performance compared to the templates containing all the minutiae from the altered fingerprints. At the threshold of 20 (i.e., minutiae templates with fewer than 20 minutiae in valid region are rejected), the CMC curves for the complete minutiae template from the altered fingerprints, the refined minutiae template by discarding minutiae in the invalid region, and their rank-level fusion are shown in Fig. 8b. The highest rank method is used for rank-level fusion. Note that the rank-1 and rank-100 identification rate at the threshold of 20 in Fig. 8a (72% and 79%, respectively) correspond to the rank-1 and rank-100 identification rate of the refined minutiae template in Fig. 8b.

Fingerprint alteration is not always successful in lowering the genuine match scores. Furthermore, the severity of the alteration does not predict degradation in matching performance. Fig. 9 shows an example where the fingerprint alteration appears to be severe due to the skin transplantation over a large area. However, it can be successfully matched to its pre-altered mate; the match score with its true mate is sufficiently high to be correctly identified at the top rank.

Removal of spurious minutiae in the altered region can improve the matching performance (see Fig. 10). In most of altered fingerprint matching, it is observed that minutiae pairing results are globally inconsistent due to a number of spurious minutiae from scars, mutilated region or background. By removing spurious minutiae, the matcher is able to find more consistent mates in minutiae pairings, which results in higher genuine match score.



(a) (b)

Figure 8. Matching performance of altered fingerprints. (a) Rejection criterion (i.e., the number of valid minutiae in the templates) versus rank-1 and rank-100 identification rate, and (b) CMC curves at the template rejection threshold of 20 minutiae in the valid fingerprint region.

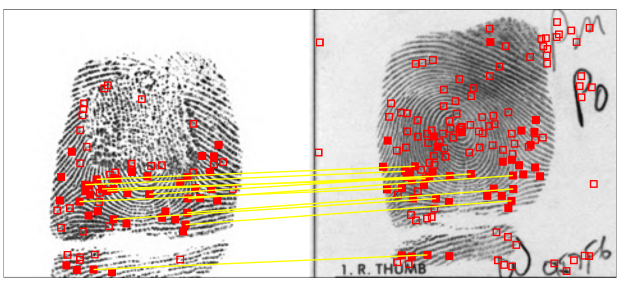


Figure 9. Example where the altered fingerprint matching is successful with all the minutiae extracted by the matcher. The match score is 287, and the pre-altered fingerprint is retrieved at rank 1 from the database with 27,382 fingerprints.

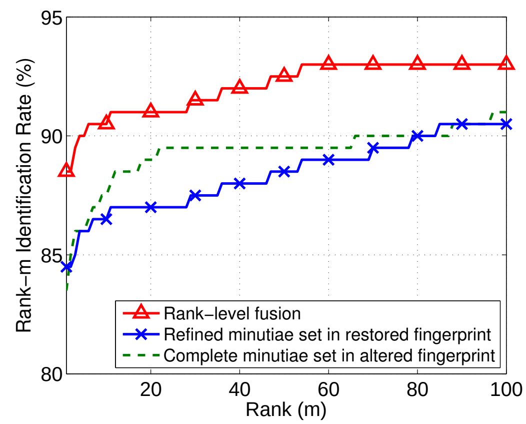


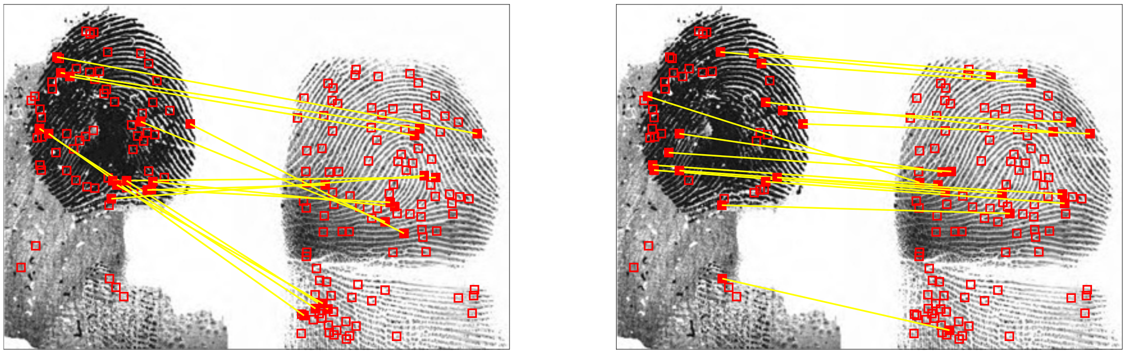
Figure 12. CMC curves for 'Z'-cut fingerprints at the template rejection threshold of 20 minutiae in valid region. While matching with the restored images alone is still challenging, the rank-level fusion of the altered fingerprints and their restored fingerprints significantly improves the matching performance.

For 'Z'-cut prints, the restoration of the distorted skin patches is helpful to improve the matching performance. Fig. 11 shows an example where ridge structures of two local patches are successfully relocated. The restored image of the altered fingerprint shows much more consistency in minutiae pairing. Further, a significantly larger number of minutiae contribute to correct matchings. The CMC curves in Fig. 12 show that the rank-level fusion of the minutiae from altered fingerprint and the minutiae from its restored fingerprint helps to improve the overall matching performance.

Altered fingerprint matching fails mainly due to: (i) insufficient number of minutiae in unaltered region which leads to rejection from minutiae-based matching, and (ii) a large amount of skin distortion that changes the structure of the neighboring minutiae (Fig. 13).

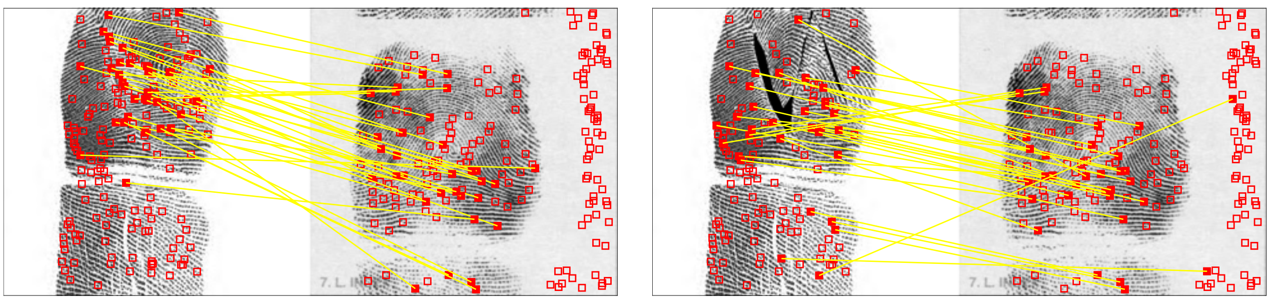
4. Conclusions and Future Work

Fingerprint alteration has received very little attention, compared to other security issues with fingerprint recognition systems such as fingerprint spoofing and template security. However, large-scale fingerprint identification systems are facing a growing threat due to fingerprint alteration since, compared to other biometric modalities (e.g., face and iris), it is relatively easier to obfuscate or alter fingerprints. Previous work on this topic [8, 13] addressed the automatic detection of altered fingerprints based on the abnormality in orientation field and minutiae distribution.



(a) (b)

Figure 10. Example where removing spurious minutiae in the invalid region improves the matching performance. (a) Matching with the complete minutiae set in the altered fingerprint (match score is 9, and the pre-altered mate is retrieved at rank 10,093), (b) matching with the refined minutiae template by removing spurious minutiae (match score is 29, and the mate is retrieved at top rank).



(a) (b)

Figure 11. Example where restoration of the 'Z'-cut fingerprint improves the matching performance. (a) Matching result of the altered fingerprint with its pre-altered mate (match score is 5 and retrieval rank is 12,525), and (b) matching result of the restored image with the mate (match score is now 51 and retrieval rank is 1).

Once altered fingerprints are detected, the subject will be sent to a secondary inspection for further investigation and for matching his altered fingerprints against the reference database. In this paper, we show that some of the altered fingerprints still have sufficient ridge information to be identified even though the severity of the alteration performed to the fingerprint appears to be large. Given a reference fingerprint database consisting of 27,000 images from NIST SD14 and 382 images from pre-altered mated fingerprint set, 86% of 1,332 altered fingerprints find their true mates within rank 100 by simply removing spurious minutiae in the invalid fingerprint region, while the minutiae templates including all the minutiae extracted from the altered fingerprint achieve 77% identification rate at rank 100. In addition, restoration of 'Z'-cut fingerprints can boost the matching performance significantly by fusing the minutiae from the altered fingerprints and their restored versions at rank-level.

Our ongoing research on matching altered fingerprints is addressing the following topics:

- Localize the altered region automatically to improve the matching performance by removing spurious minutiae in the altered region as well as classify 'Z'-cut cases which are of special interest due to the possibility of restoration;

- Develop a new fingerprint matching algorithm specialized to altered fingerprint matching which is robust to skin distortion and that maximally uses local ridge structure in valid fingerprint region.

Acknowledgements

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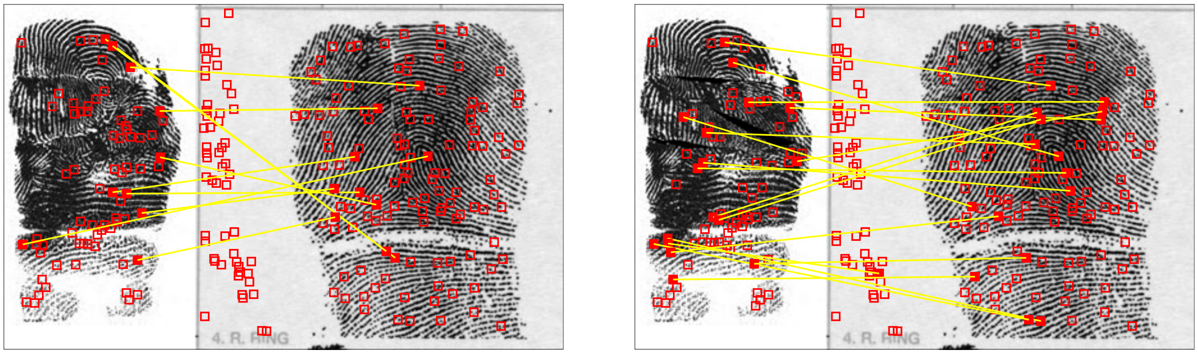

(a) (b)

Figure 13. Example where the altered fingerprints cannot be correctly matched with their true mates using any refined minutiae templates. (a) Refined template from altered image and (b) refined template from restored image. Match scores for each pair in (a) and (b) are 3 and 9, respectively. Due to the large amount of skin distortion, none of these methods are successful in finding the correct mate within a practical size of the candidate list.

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