Fingerprint Matching with Optical Coherence Tomography

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Abstract. Fingerprint recognition is an important security technique with a steadily growing usage for the identification and verification of individuals. However, current fingerprint acquisition systems have certain disadvantages, which include the requirements of physical contact with the acquisition device, and the presence of undesirable artefacts, such as scars, on the surface of the fingerprint. This paper evaluates the accuracy of a complete framework for the capturing of undamaged, undistorted fingerprints from below the skins surface using optical coherence tomography hardware, the extraction and conversion of the subsurface data into a usable fingerprint and the matching of such fingerprints. The ability of the framework to integrate with existing fingerprint recognition systems and its ability to operate as an independent stand-alone system are both evaluated.

1 Introduction

1.1 Fingerprint Matching

Fingerprint matching is a biometric technique that is often used for the identification or verification of individuals. It is used for access control to physical areas, such as at the entrances to buildings; for access to virtual areas, such as unlocking virtual devices; in forensics and the criminal justice system; and for border control. It is also use in authentication systems, such as verification during the transfer of electronic funds [1].

Fingerprint recognition requires the extraction and matching of minutia details from the fingerprint. The most common minutiae used in fingerprint recognition are ridge endings and bifurcations. A ridge ending is a point where a ridge stops. A bifurcation is a point where a ridge splits into two separate ridges. Fig. 2(a) shows examples of ridge endings and bifurcations. These are collected from the surface of a users finger. A user presses their finger against the platen of a surface scanner and the fingerprint is scanned.

However, the fingerprints on the surface of the skin originate below the surface of the skin, in the papillary layer. The fingerprint patterns are formed at the papillary junction, which is the junction of the dermal layer and the papillary layer [1] [2]. Through the use of optical coherence tomography (OCT), the subsurface information of the fingerprint can be extracted and used. Several advantages of OCT over conventional surface fingerprint scanners are discussed below.

1.2 Optical Coherence Tomography

OCT is a non-invasive, non-contact, optical imaging technique that is able to yield sub-surface morphology (2D or 3D) of scattering samples in situ and in real time. OCT is often described as the optical analogue to ultrasound. However the back scattered light cannot be measured electronically due to the high speed of light. Therefore OCT uses the technique of low coherence interferometry, first demonstrated by Huang in 1991 [3]. Since then it has been applied extensively in biomedical applications especially ophthalmology, dermatology and cardiology [4] [5] [6] [7] with some applications in material science and in artwork and has in the last few years been gaining momentum in the field of biometrics [8].

The advantage of OCT over other biometric techniques lies in its inherent ability to deliver contactless, subsurface 3D fingerprints with high resolution. The 3D capability allows one to differentiate between a real and a fake fingerprint to counter identity theft spoofing attacks [8] and also allows for the detection of the inner subsurface fingerprint which is a replica of the outer fingerprint. By using OCT technology, the fingerprint patterns can be extracted from the papillary junction (PJ). The fingerprints found at the papillary junction are unaffected by scarring, cuts and wrinkles that are present on the surface of the skin. This invariance allows PJ fingerprints to have a greater clarity and greater reliability than surface fingerprints. This is also an advantage for people such as miners and people who are subject to extensive manual labour or old age whose outer fingerprints are less readable by conventional surface scanners due to abrasions, scars and wrinkles.

Due to the contactless nature of OCT technology, fingerprints will not experience the distortion that occurs when fingers are pressed against a surface, as occurs with conventional surface contact scanners [9]; and it may also be used in environments in which contact with surfaces is detrimental, such as at access points to sterile operating theatres or laboratories.

Furthermore, while compliance with FBI standards requires a resolution of 500 dots per inch (dpi) for fingerprint scanners, there is a growing trend towards higher resolutions or 1,000 dpi. Greater resolutions allow for accurate detection of incipient ridges and sweat pores, which allows for great accuracy in fingerprint recognition [1]. OCT technology is capable of detecting sweat pores on the surface of fingerprints, as well as the subsurface eccrine glands from which the pores originate [10]. Doppler OCT scanners are also capable of resolutions greater than 10,000 dpi, which are fine enough and with non-invasive optical penetration deep enough to detect the blood capillaries below the fingerprint [11]. This may be used for liveness detection, and as a further biometric recognition modality.

While techniques for the extraction of fingerprints have been described [12], little has been done to evaluate the ability to match these extracted fingerprints against both legacy surface fingerprints, as well as other extracted OCT fingerprints. The remainder of this paper describes a framework for the detection and extraction of information from the papillary junction, mapping of the extracted 3D fingerprint to a 2D image, and extraction and matching of fingerprint minutiae. Subsurface OCT fingerprints obtained in this manner are compared against surface fingerprints and other subsurface fingerprints to determine the reliability of this technique.

2 Methodology

2.1 Fingerprint Extraction

The process for the capturing and extraction and matching of OCT fingerprints is shown in Fig. 1. Fingerprints are captured using a Swept Source Optical Coherence Tomography (SSOCT) device (Model OCM1300SS) - Thorlabs Inc., USA. The system consists of a laser source that scans in over a wavelength band (frequency band). The centre wavelength is 1325nm, scanning 110 nm around the central wavelength with a spectral width of 3dB spectral bandwidth. The system resolution is 15- 20 um with a probing depth of 3 mm in air. The laser output power is 10 mW with a coherence length of 6 mm and an axial scan speed of 16 kHz. It can image a physical volume of $15 \times 15 \times \sim 3mm^3$ with a representation of $512 \times 512 \times 512$ pixels (867 pixels per inch) in approximately 22 seconds; and a volume of $13 \times 13 \times \sim 3mm^3$ with a representation of $256 \times 256 \times 512$ pixels (500 pixels per inch) in approximately 6 seconds . The papillary junction (PJ) is extracted, using a technique similar to Akhoury and Darlow [12], in which the stratum corneum is first detected. Using the stratum corneum as a reference point, the papillary junction is then detected and extracted, to form a three dimensional structure.

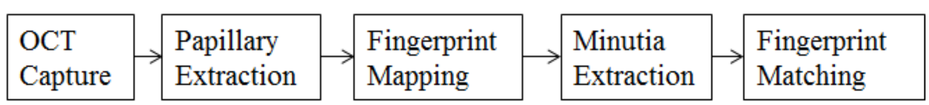

Fig. 1. An overview of the process for fingerprint matching using OCT technology

Fig. 2(b) shows a slice of a finger from an OCT image. The papillary junction is outlined with a solid line. This junction has a wave-like form due to the existence of ridges and valleys. This is the micro-curvature of the finger. A broken line represents the greater overall curvature of the finger, which is due to its approximately cylindrical nature. This is the macro-curvature of the finger. For accurate mapping of the 3D structure into 2D, the macro-curvature needs to be eliminated, while the micro-curvature information of ridges and valleys needs to be maintained. This conversion is performed, by projecting the 3D structure onto a 2D plane, as described in Akhoury and Darlow [12].

Since the OCT images are degraded by speckle noise, it is natural to anticipate the effects of such artefacts to influence the location of the algorithmically

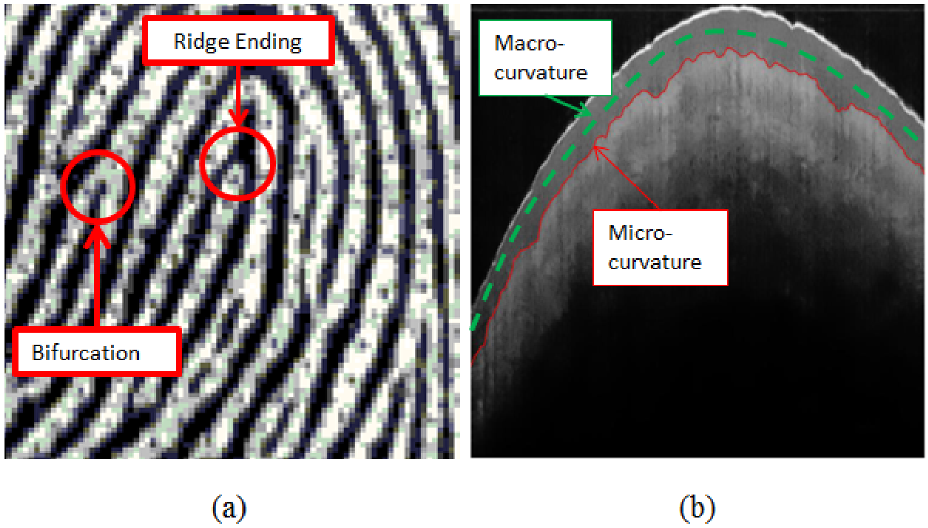

Fig. 2. *(a)* A sample fingerprint with a ridge ending and a bifurcation highlighted. *(b)* A sample slice of an OCT scan from a tip-on view. The *thick white line* represents the skins surface. Data below the *thick white line* is subsurface information collected using an OCT scanner. The *green dashed line* depicts the macro-curvature of a finger and the *solid red line* depicts the micro-curvature created by the fingerprint pattern.

determined papillary junction contours. Hence, prior to any further processing - errors in the detected contours must be accounted for. This is done by applying the non-linear median filter. The resultant surface is a smoothed 3D representation of the ridges and valleys of the fingerprint from the internal fingerprint. The ridge-valley fingerprint structure is situated along the varying depth dimension of the finger. As we are only concerned with the peak-crest sinusoidal-like pattern of the ridge-valley structure, the effects of the varying depth parameter can be eliminated by differentiation. In image processing, this is more formally known as edge detection. As in Akhoury and Darlow [10], we also apply the phase congruency approach [13]. The resultant derivatives are then exemplified by a sigmoid function in an attempt to amplify the low powered sinusoidal pattern. A second stage non-linear median filter is then applied to smooth the contours and remove anomalous saturated peaks. The resultant signal is then enhancement using contrast-limited adaptive histogram equalization (CLAHE) [14] and contrast stretching.

Once the fingerprint is successfully converted into a 2D format, fingerprint minutiae may be extracted. Once the minutiae are extracted from two fingerprints, these fingerprints may be matched. The extraction and matching of minutiae is thoroughly covered in literature and there are many commercial solutions available [1] [15].

2.2 Parameter Optimization

The framework for the mapping from a three dimensional (3D) structure to a two dimensional (2D) image, contains a very large set of parameters. In order to determine the best values for each of these parameters, search optimization techniques may be used. The chosen technique must find an optimal combination of values for each parameter such that the ideal 2D image of the fingerprint is acquired. An example of common search optimization technique in such cases is the genetic algorithm, which mimics evolution theory. It is a stochastic approach used to search a wide space of unknown gradient, and reduces to an optimal solution while overcoming the risks that local minima present to search techniques [16] [17].

Key to designing an effective genetic algorithm is determining the objective function, which evaluates the overall score for each combination of parameter values. In this case, the objective function was implemented to optimize the match score between the mapped 2D fingerprint and a conventional contact surface fingerprint.

3 Results and Discussion

Two sets of tests were performed. In the first set of tests, the PJ fingerprints, extracted from below the surface of the skin using OCT technology, were compared against surface fingerprints, which are collected using a surface fingerprint scanner. This is used to evaluate the accuracy of matching between OCT and contact surface fingerprints for the purposes of backwards compatibility with existing fingerprint recognition systems. These comparisons were performed against 22 fingers of various individuals.

In the second set of tests, two OCT samples were collected from each of 5 fingers. The samples were compared against each other to evaluate the potential accuracy of a system in which fingerprint recognition is performed using contactless PJ fingerprints only.

The performance of matching before and after parameter optimization is also evaluated. Due to the newness and novelty of the hardware technology and extraction technique, there are currently no publicly available databases of OCT fingerprints. Data sets were collected by the research team, conforming to the South African Protection of Personal Information Act [18].

3.1 Papillary Junction Compared to Surface Fingerprints

Subsurface scans of 22 fingers were collected from various individuals using the hardware described in Section 2.1. In the first 12 samples, an area of $15 \times 15mm^2$ was captured at 867dpi and subsequently scaled down to 500dpi. In samples 13 to 22, an area of $13 \times 13mm^2$ was captured at 500dpi. Surface scans of the fingers, using contact fingerprint scanners, were also obtained for matching comparisons.

The internal subsurface fingerprints were extracted and mapped to a 2D plane, using parameters which were optimized as described in Section 2.2. The minutia extraction and matching was performed using the SecuGen Software Development Kit [19]. Fig. 3 shows a comparison of a subsurface fingerprint mapped to 2D using random unoptimized parameters in Fig. 3(a), and optimized parameters in Fig. 3(b). In Fig. 3(a), data is lost during the mapping process, due to using sub-optimal parameters. With optimized parameters, in Fig. 3(b), the ridges and valleys are more clearly defined and sufficient information is retained to accurately detect ridge ending and bifurcation minutia points. In Fig. 3(c), a surface scan of the same fingerprint, taken with a conventional surface scanner, is shown. The detected minutia points are marked with circles. There is a high similarity between the optimized subsurface fingerprint and the surface fingerprint. Additionally, the subsurface fingerprint is free of the scarring that is visible on the surface fingerprint.

Table 1 shows a comparison of acceptance and rejection rates for both the optimized and unoptimized parameters when matched against surface fingerprints. 22 true comparisons were performed, by comparing the collected subsurface OCT fingerprints with the corresponding surface scanner fingerprints. 462 false comparisons were performed, by comparing each of the 22 subsurface OCT fingerprints with each of the other 21 non-corresponding surface scanner fingerprints. While no false matches were accepted, several true matches were rejected. However, the parameter optimization reduced the false rejection rate and improved true acceptance. Fig. 4 shows a comparison of the match scores before and after the optimized parameters were determined. Optimizing the parameters improved the accuracy of matching in all cases. It is seen that match scores in some cases were still below the threshold which determines whether a match is accepted or not. This undesirable outcome may be caused by several factors: errors in capturing, and errors in mapping from 3D to 2D. Descriptions of the source of the errors and proposed solutions to mitigate them are provided below.

There are two known errors which may occur during the capturing process. The first of these is caused by excessive movement of the finger during capturing, since it is difficult to keep a finger still during a lengthy capturing time. The second is due to the maximum scanning depth of the OCT hardware. The scanning depth is set at a pre-determined value prior to the initiation of the capturing sequence. However, due to the irregular cylindrical nature of a finger in three-dimensional space, parts of the finger may be outside of the depth range of the scanner. This leads to a reduction in the total scanned area. A reduced area leads to a lower number of detected minutia points, which in turn reduces the ability to accurately match two fingerprints. This problem is called the depth dependency roll-off. Both of these known errors may be countered by the use of better hardware.

The current drive in OCT technology is to develop systems that can scan faster so as to remove motion artefacts and that is able to penetrate deeper into the sample. The SSOCT system offers the fastest scan times which are dependent on the sweeping speed of the laser used. The system used for this study had a scan speed of 16 kHz. The very same system can be implemented with higher scan rates from newly available or soon to be available sources [20] [21]. One such source is source with a 200 kHz scan speed theoretically resulting in a 12.5× decrease in acquisition time. Such a laser, which is available from Thorlabs Inc., USA, also has an imaging depth of at least 12 mm. Currently, faster speeds are limited by the available detection electronics so there is a possibility of even faster and more efficient systems in the not so distant future. The goal is to reduce capturing time to a speed of less than 1 second, which is compatible with current fingerprint capturing standards [1]. A faster acquisition time and greater scanning depth would eliminate the errors which occur during the capturing process and thus improve the matchability of the fingerprints.

Improvements in the mapping of 3D to 2D may also have an impact on the matching. Currently, the 3D structure is projected directly onto a plane. However, direct projection may impact the perceived distance between ridges and the thickness of ridges. Additionally, due to the elastic nature of the skin, distortions occur in touch-based fingerprint matching. Ridges contract at the first point of contact with a surface, and expand further out. The touchless OCT fingerprint acquisition system is free from such distortions. Techniques similar to those employed by Zhao et al. [9], which take into consideration the macro-curvature of the finger and model the distortions of the skin may allow for better matching and better backwards compatibility of touchless subsurface fingerprints with the conventional touch-based surface fingerprint scanners.

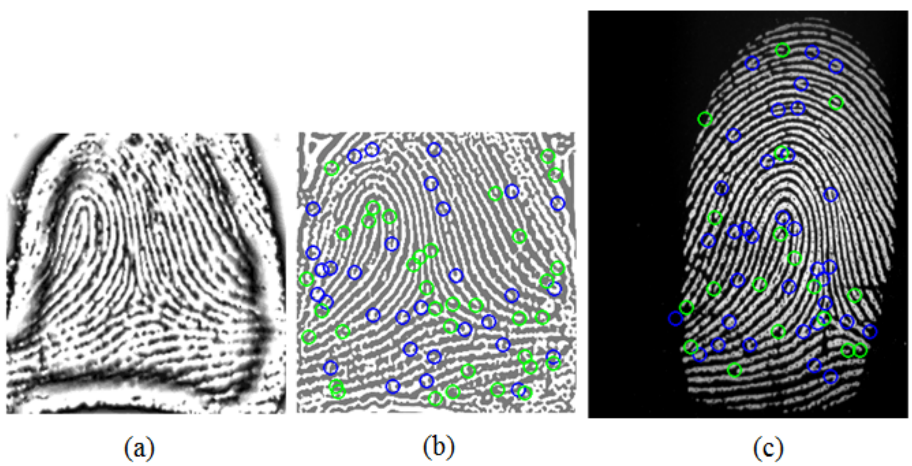

Fig. 3. A comparison of subsurface OCT scanner derived and conventional surface scanner fingerprints. *(a)* shows an OCT subsurface fingerprint before parameter optimization; *(b)* shows an OCT subsurface fingerprint after parameter optimization; and *(c)* shows a surface fingerprint from a conventional scanner. The *blue circles* signify detected ridge bifurcations, and the *green circles* signify detected ridge endings

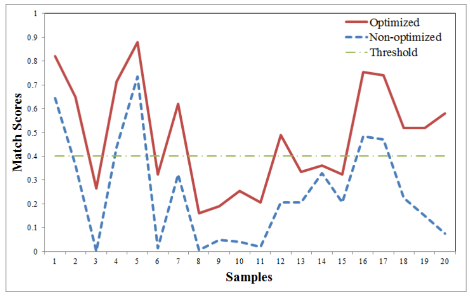

Fig. 4. A comparison of scores for the matching of OCT derived subsurface fingerprints using random unoptimized parameters and optimized parameters against corresponding conventionally scanned surface fingerprints

Table 1. A comparison of acceptance and rejection rates for the matching of optimized and unoptimized OCT fingerprints against conventional surface scanned fingerprints

	Unoptimized		**Optimized**	
	Acceptance \%	**Rejection** \%	**Acceptance** \%	**Rejection** \%
False	0	77	0	41
True	23	100	59	100

3.2 Papillary Junction Compared Against Other Papillary Junction Fingerprints

For these tests, 10 samples were collected, with 2 each per finger, with a physical coverage of $13 \times 13mm^2$ at 500dpi. The subsurface fingerprints from the papillary junction were extracted from each and compared against each other. Fig. 5 shows a visual comparison of two fingerprints captured in this manner. The two captured fingerprints are almost identical in nature which results in a very high match score. Since both fingerprints were captured using a contactless system, neither fingerprint suffers from the adverse effects of distortion which plagues touch-based fingerprint scanners. The quality of surface scanned fingerprints is also affected by the dryness of the users finger and the pressure applied. If a finger is too dry or if too little pressure is applied, the ridges will be discontinuous. With too much pressure, the width of detected ridges increases and causes valleys to become indistinct. The contactless OCT scanner is not affected by these factors.

Table 2 shows a comparison of acceptance and rejection rates for both the optimized and unoptimized parameters when subsurface fingerprints were matched against other subsurface fingerprints. 5 true comparisons were performed, by comparing two collected subsurface OCT fingerprints with each other for each finger. 80 false comparisons were performed, by comparing the two OCT fingerprints of each finger with each of the other 8 non-corresponding OCT subsurface fingerprints. While no false matches were accepted, several true matches were rejected. However, as with the surface comparisons, the parameter optimization reduced the false rejection rate and improved true acceptance. Fig. 6 shows a comparison of matching for each finger. As before, parameter optimization improved the results in all cases. The two lowest scores (for samples 2 and 5) were due to depth dependence roll-off. Hardware solutions to counteract this issue were discussed in the previous section. Due to the large capturing area; lack of distortion, which occurs in contact-based systems; elimination of surface artefacts; and the potential for higher resolution data capture, the matching together of PJ fingerprints, captured with OCT technology, has the potential to provide more accurate fingerprint recognition than comparisons with surface fingerprints.

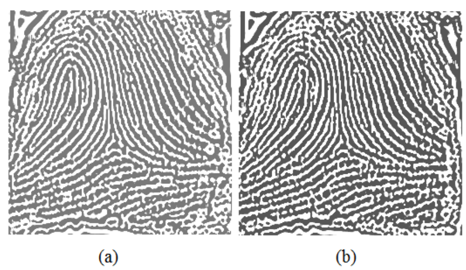

Fig. 5. Comparison of two separate OCT scans of the same finger, showing a very high match

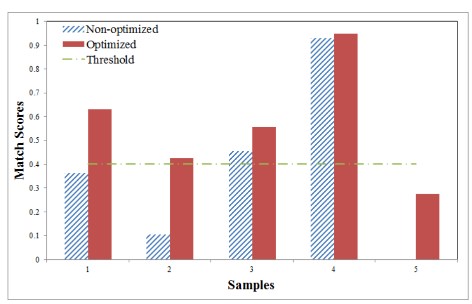

Fig. 6. A comparison of scores for the matching of OCT derived subsurface fingerprints using random unoptimized parameters and optimized parameters against other OCT derived prints from the same fingers

These preliminary studies show promise for a subsurface fingerprint matching system. Further statistical analysis of the parameter optimization and the match scores of the proposed system will be performed once a larger dataset is collected.

Table 2. A comparison of acceptance and rejection rates for the matching of optimized and unoptimized OCT fingerprints against other OCT derived fingerrints

	Unoptimized		**Optimized**	
	Acceptance \%	**Rejection \%**	**Acceptance \%**	**Rejection \%**
False	0	60	0	20
True	40	100	80	100

4 Conclusion

It has been shown that the subsurface papillary junction fingerprint captured using OCT technology can be matched with surface fingerprints with a high degree of reliability. Further, this can be reproduced by the ability to match subsurface fingerprints with each other. The proposed framework has several advantages over current fingerprint acquisition systems, which include the elimination of surface artefacts, the avoidance of distortion which is introduced by surface contact acquisition devices, and the ability to capture greater details at higher resolutions. Improvements to the current hardware system have also been proposed to increase the quality of the capturing process and subsequently improve the reliability of matching.

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