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Contrast Enhanced Subsurface Fingerprint Detection using High-speed Optical Coherence Tomography

Xiaojun Yu, Qiaozhou Xiong, Yuemei Luo, Nanshuo Wang, Lulu Wang, Hong Liang Tey, and Linbo Liu

Abstract—Spectral-domain optical coherence tomography (SD-OCT) has been demonstrated to be a viable tool in forensic science for fingerprint detection, yet it still suffers from certain practical issues, e.g., the limited scanning speed and low image contrast. In this letter, we report a high-speed SD-OCT together with an image contrast enhancement mechanism for reliable subsurface fingerprint detection. The constructed SD-OCT system achieves a scanning rate up to 60K A-lines/s, and thus, both 3D volumetric images, reaching up to $20\text{mm} \times 20\text{mm} \times 1.2\text{mm}$, and *en face* internal fingerprint furrow pattern images could be obtained. Based upon the analyses of the papillary layer anatomical structures, the contrast enhancement technique not only suppresses image artifacts, but also is effective in detecting fingerprint spoofing. Experiments on healthy subjects have also been conducted to verify the system imaging capability and the effectiveness of the contrast-enhancement technique.

Index Terms—Biometrics, fingerprint identification, optical coherence tomography (OCT).

I. INTRODUCTION

FINGERPRINT recognition is a commonly used biometric technique for both individual identification and security control. Due to its advantages of universality, uniqueness and accuracy over the other methods, it has been widely adopted in various areas, and currently, numerous systems, sensors, as well as recognition algorithms have been developed [1]. Based mainly on surface topography analysis, however, most of the existing fingerprint recognition techniques are prone to both spoofing attacks like fake or dead fingers, and fingertip surface conditions, e.g., scars/injuries on the fingertips, wet or fuzzy fingerprints, etc. Such issues prevent the conventional finger-readers from reading the fingerprints. To address these issues, new technologies, such as iris recognition [2], vein pattern recognition [3], and nailbed identification [4], etc., have also been proposed. However, since those methods still rely on 2D biometric feature analysis, and cannot provide any depth-resolved information, they are still prone to spoofing attacks. Furthermore, the lack of existing databases is another big issue.

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Optical coherence tomography (OCT) is a non-invasive imaging modality capable of providing both cross-sectional and 3D tissue images [5]. Over the past decade, OCT has not only been used as a routine clinical tool for diagnosis of ophthalmic and skin diseases, but also been utilized as an imaging tool in some other fields, e.g., in forensic science for fingerprint detection [6–14]. Cheng *et al.* employed a time-domain OCT (TD-OCT) to identify the artificial and real fingerprints with depth-resolved 2D and 3D fingerprint images [6]. With a spectral-domain OCT (SD-OCT), Bossen *et al.* verified the feasibility of using papillary layer structures for fingerprint recognition [7], while Liu *et al.* showed the applicability of using subsurface sweat glands distribution for identification [14]. By utilizing high-speed line cameras, Aum *et al.* realized live fingerprint acquisition at a scanning rate of 92K A-lines/s with a graphics processing unit (GPU) integrated onto SD-OCT for data processing [13], while Breithaupt *et al.* achieved an acquisition rate of 80K A-lines/s with a swept-source OCT (SS-OCT) [12]. Full-field OCT (FF-OCT) was also proved to be a viable tool for fingerprint identification [8], and has been utilized either for latent fingerprint detection with minor changes [9], or for exemplar sweat pores and internal fingerprint imaging with fast speed [10] (Review on OCT as a tool for fingerprint detection could be found in [11]). It is worth noting that although FF-OCT acquires *en face* images much faster than SD-OCT, it is much slower than SD-OCT for 3D image acquisitions. Previously reported TD- and SD-OCT provide depth-resolved information [15], yet they suffer from limited imaging speed and image contrast. In addition, existing OCT based fingerprint detection methods do not demonstrate the capability of suppressing image artifacts (such as scars, ducts and water drops on the fingertips), which in turn may compromise the detection accuracy and/or efficiency.

In this letter, we report a high-speed SD-OCT system that is capable of detecting contrast-enhanced and artifact-suppressed subsurface fingerprints. The system acquisition rate is 60K A-lines/s. To enhance *en face* fingerprint image contrast while removing artifacts, an image processing method based on the analyses of papillary layer anatomical structures is also presented. Experiments were conducted to verify the system imaging capability and effectiveness of the proposed method in different cases.

II. EXPERIMENTAL SETUP AND PROCESSING METHOD

A. OCT System

Fig. 1(a) shows the constructed fiber based SD-OCT system. A broadband light source (Superlum Broadlighters T-850-HP)

with a center wavelength of $\lambda_c = 850\text{nm}$ and a full-width at half maximum (FWHM) bandwidth of $\Delta\lambda = 165\text{nm}$ was used. The 21.2mW source output was split by a broadband 50:50 fiber coupler (TW850R5A2, Thorlabs Inc.) with one portion directed to the sample arm and the other to the reference arm. The sample arm was formed to be a portable handheld probe as shown in Fig. 1(b). It consists of a collimation lens L3 (AC080-015-B-ML, Thorlabs Inc.), a galvo scanner (GVSM002/M, Thorlabs Inc.) and an objective lens L4 (AC254-050-B-ML, Thorlabs Inc.). Specifically, at the tip of the probe, a 3mm thick glass window W2 was placed after L4 with its second surface positioned $\sim 200\mu\text{m}$ before the focal plane, such that the scanning beam was approximately focused at the papillary junction when W2 is in direct contact with the finger. The reference arm consisted of a polarization controller, a lens L1 (identical to L3), a glass window W1 (identical to W2 for dispersion compensation), a lens L2 (identical to L4) and a mirror M1.

Fig. 1. OCT system constructed. (a) System schematic. (b) Portable handheld probe. PC: polarization controller; SMF: single-mode-fiber; L1-5: achromatic lenses; L6: camera lens; W1-2: glass window; M1: reference mirror.

The interference signals were guided to a spectrometer, which consists of a collimation lens L5 (AC127-030-B-ML, Thorlabs Inc.), a diffraction grating (1200 l/mm@830nm, Wasatch Photonics Inc.), a camera lens (Nikon AF Nikkor 85mm f/1.8D), and a line scanned camera (E2V, AViVA EM4). The spectrometer efficiency, including the grating efficiency and the overall losses of optical components, was measured to be 0.424. The detected signals were transferred to a computer through camera link cables and an image acquisition card (KBN-PCE-CL4-F, Bitflow Inc.) at 12-bit digital resolution. In the experiments, both camera and galvo scanners were synchronized by a computer generated triggering signal. The effective camera pixel number was measured to be 1286 at FWHM, and the sample power was measured to be 6.75mW.

B. System Performance

Fig. 2(a) shows an *en face* image of a resolution chart. When enlarged as shown in the inset, the line pattern of group 6 element 1 with a line spacing of $7.81\mu\text{m}$ could be resolved, demonstrating that the system lateral resolution is $\sim 7.8\mu\text{m}$. To measure the axial resolution, we inserted an actuated iris diaphragm (SM05D5, Thorlabs Inc.) with a total attenuation of 35.6dB into the sample arm optics, and acquired an A-line profile by placing a partial reflector ($\sim 14\text{dB}$) at the focal plane. The obtained point spread function (PSF) of an A-line profile (Fig. 2(b)) shows that an axial resolution of $\sim 2.3\mu\text{m}$ was achieved in air. Such results matched our predicted values of $9.8\mu\text{m}$ and $1.9\mu\text{m}$, respectively. Moreover, as the signal-to-noise ratio (SNR) was measured to be 54.6 dB at $80\mu\text{m}$

length difference with an illumination power of 0.701mW, the system sensitivity was estimated to be $\sim 104.2\text{dB}$, which was slightly lower than the theoretical value of 105.5dB.

Fig. 2. System spatial resolution characterization. (a) *En face* image (3072 pixels $\times$ 3072 pixels, $13.1\text{ mm} \times 13.1\text{ mm}$) of the 1951 USAF resolution chart. Inset: enlarged image with scanning area of $1.3\text{ mm} \times 1.3\text{ mm}$. (b) Measured axial PSF of the constructed OCT system.

C. Data Acquisition and Image Processing

The papillary layer located at the junction of epidermis and dermis layers is the origin of the external fingerprints, and was usually utilized for internal fingerprint detection. In this study, a number of cross-sectional fingertip images were acquired first to generate 3D images, and then *en face* fingerprint images at the papillary junction were extracted for processing.

Fig. 3. Cross-sectional image of a volunteer's thumb (3, 072 pixels $\times$ 1, 325 pixels for 13.1 mm (W) $\times$ 1.15 mm (D)).

Fig. 3 presents a typical cross-sectional fingertip image. As seen, the shape of the papillary layer is exactly the same as that of the epidermis, formed by papillae ridges and valleys. The papillary junction is $\sim 0.2\text{mm}$ below the skin surface with a thickness of $\sim 0.55\text{mm}$ in this study. Such a junction area can be further divided into ridge and valley portions. While the ridge portion is defined as the structure from the tops of the papillae ridges to the bottoms of the papillae valleys, the valley portion is from the top of the papillae valleys to the bottom of the papillary junction. Hence, in the *en face* images, the ridge portion and the valley portion are opposed in intensity.

Inspired by such a fact, we proposed a contrast enhancement mechanism: by performing a simple differential operation between *en face* images of the ridge and the valley portions, the papillary structure signals can be doubled while their “common mode” artifacts can be largely suppressed or even removed, and finally, contrast of the subsurface fingerprint images can be enhanced. The ImageJ software was utilized for processing. In our study, the average of *en face* image

slices (starting from the glass surface) from 410 to 585 was utilized as the ridge portion image, while the average of those from 585 to 945 was utilized as the valley portion image. It is worth mentioning that due to the differences in skin elastics, such image slices may represent different skin depths among different individuals.

III. RESULTS AND DISCUSSIONS

In the study, a skin gel (Aquasonic 100, Parker Laboratories Inc.) was applied onto the fingertip to prevent refractive index mismatching between the skin and the glass window when imaging. Fig. 4 presents a 3D thumb image reconstructed from a number of cross-sectional images acquired, and its size reaches up to $20\text{mm} \times 20\text{mm} \times 1.2\text{mm}$ (XYZ, $2048 \times 2048 \times 1380$ pixels). As shown, the fingerprint can be clearly resolved. Fig. 4(a) depicts a small portion of the thumb tissue with a volume of $4.4\text{mm} \times 4.4\text{mm} \times 0.7\text{mm}$ (XYZ). Its contrast was adjusted such that the individual spiral sweat ducts could be clearly resolved. It is worth mentioning that since the thumb's pressure on the glass window was not uniform while imaging, the reconstructed 3D image appears to be not flat at the corners, yet it did not introduce any side effects.

Fig. 4. Volumetric image of a volunteer's thumb. (a) Enlarged 3D image of the selected area with individual spiral sweat glands resolved.

En face fingerprint images were extracted with the obtained 3D images. Fig. 5(a) presents an *en face* subsurface fingerprint image of a volunteer's thumb at the papillary ridge portion. It was averaged over an imaging depth from 0.23mm to 0.33mm. As seen, the furrow pattern could be resolved even though the image contrast is not good enough at certain areas. It again demonstrated that the subsurface fingerprint obtained with OCT could be utilized for identification purpose. However, it is also worth noting that in such an image there exist surface scars and blurring areas (as marked), or water drops within the finger furrows, which would introduce artifacts and finally cause misleading results if the image was used for identification purpose.

To alleviate the influences of such artifacts while improving image contrast to facilitate identification, the proposed contrast enhancement mechanism was applied. Fig. 5(b) shows an *en face* image of the same finger at the valley portion averaged over the depth from 0.33mm to 0.54mm. Results showed that the furrow pattern could be identified and matched exactly with that in Fig. 5(a), although the pattern color was opposite.

After performing a standard deviation between the two images, Fig. 5(c) was obtained, showing that the artifacts introduced by the surface scars were eliminated, and the structural details at the blurring areas were extracted clearly. Image contrast was also largely enhanced. In addition, the sweat pore distribution shown in Fig. 5(d), which was extracted at a depth from 0.15mm to 0.22mm, could also be utilized as a supplementary for identification purpose.

Fig. 5. *En face* subsurface fingerprint images of a volunteer's thumb (a-d: $8.72\text{mm} \times 8.72\text{mm}$, 2048×2048 pixels). (a) Ridge portion image averaged over an imaging depth from 0.23mm to 0.33mm. (b) Valley portion image averaged over an imaging depth from 0.33mm to 0.54mm. (c) Image obtained after performing contrast enhancement mechanism. (d) Sweat pores distributed between the epidermis and dermis layers (0.15mm to 0.22mm)

Scars are typically surface modifications to the fingertips, affecting the conventional fingerprint scanners with introduced artifacts. To further verify the effectiveness of the proposed method in suppressing artifacts, a transparent sticker glue was placed onto the volunteer's thumb surface to simulate a scar (Fig. 6(a)). Figs. 6(b) and 6(c) show the obtained *en face* images of the ridge and valley portions, which were averaged over imaging depths from 0.24mm to 0.37mm and 0.37mm to 0.61mm, respectively. Results showed that both sticker glue and water drop artifacts were observed, which changed the furrow pattern. Once the proposed technique was performed between those two images, however, the artifacts were removed and the contrast was largely enhanced as shown in Fig. 6(d). The sweat duct pores were also clearly observed.

We also conducted experiments to verify the reliability of the proposed method against spoofing attacks using fingerprint dummies. A small amount of wax with a thickness of $\sim 2.5\text{mm}$ was melted to mix with household cement first, and then the thumb of a volunteer was pressed firmly into the wax to leave a clear fingerprint. Such a wax dummy then was scanned with OCT. Fig. 7(a) shows the surface image of the dummy finger. Figs. 7(b) and 7(c) show *en face* OCT images of the dummy, which were averaged over imaging depths from 0.24mm to 0.37mm and 0.37mm to 0.61mm, respectively. Results showed that fingerprints in both images could be resolved, and matched with the surface image. However, once the proposed technique was performed between Figs. 7(b) and 7(c), the furrow pattern no longer exist, as seen in Fig. 7(d). The same results were

Fig. 6. Surface artifacts suppression (a-d: $8.72\text{mm} \times 8.72\text{mm}$, 2560×2560 pixels). (a) *En face* surface image of a volunteer's thumb. (b) Subsurface image averaged over depth from 0.24mm to 0.37mm. (c) Subsurface image averaged over depth from 0.37mm to 0.61mm. (d) Obtained contrast enhanced image.

also observed when the above experiments were conducted with other volunteers, or at lower system acquisition rates.

Fig. 7. Dummy fingerprint for spoofing identification. (a) Surface image of the dummy fingerprint. (b) Subsurface image averaged over a depth from 0.24mm to 0.37mm. (c) Subsurface image averaged over a depth from 0.37mm to 0.61mm. (d) Image obtained after performing contrast enhancement method. (b-c: $10.5\text{mm} \times 10.5\text{mm}$, 1024×1024 pixels).

The main factor limiting practical application of SD-OCT is still its scanning speed, e.g., it took 70s, 110s and 17.5s to obtain 3D images for Figs. 5, 6 and 7, respectively. Such an issue is even more serious when A-line number is larger for a frame. To address such an issue, high-speed SS-OCT could be a candidate solution. High-speed line cameras [12, 13] and scanning mirror [16] are also needed. While for the contrast enhancement method, the main issue is the varying depths of the papillary ridge and valley portions among different individuals, and thus, efficient algorithms to locate such structural portions have to be developed in the future.

IV. CONCLUSION

A high-speed SD-OCT together with a contrast enhancement mechanism for reliable fingerprint detection was reported

in this letter. Experiments were also conducted to demonstrate the imaging capability of the system and the effectiveness of the proposed contrast enhancement technique. Results showed that such an OCT is able to acquire volumetric image up to $20\text{mm} \times 20\text{mm} \times 1.2\text{mm}$ at an acquisition rate of 60K A-lines/s. The proposed contrast enhancement technique not only largely improves the image contrast but also reduces the influences of artifacts, and is also effective in detecting spoofing. Such features enable the fingerprint identification process to be much easier and more robust. There is great potential for OCT to be used for practical applications in forensic science.

REFERENCES

- [1] D. Maltoni, D. Maio, A. Jain, and S. Prabhakar, *Handbook of fingerprint recognition*. Springer Science & Business Media, 2009.
- [2] A. Ross, "Iris recognition: The path forward," *Computer*, vol. 43, no. 2, pp. 30–35, 2010.
- [3] C. Wilson, *Vein pattern recognition: a privacy-enhancing biometric*. CRC press, 2010.
- [4] A. Topping, V. Kupersmidt, and A. Gormley, "Method and apparatus for the automated identification of individuals by the nail beds of their fingernails," May 12 1998, uS Patent 5,751,835.
- [5] D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito *et al.*, "Optical coherence tomography," *Science (New York, NY)*, vol. 254, no. 5035, p. 1178, 1991.
- [6] Y. Cheng and K. V. Larin, "In vivo two- and three-dimensional imaging of artificial and real fingerprints with optical coherence tomography," *IEEE Photonics Technology Letters*, vol. 19, no. 20, pp. 1634–1636, 2007.
- [7] A. Bossen, R. Lehmann, and C. Meier, "Internal fingerprint identification with optical coherence tomography," *IEEE Photonics Technology Letters*, vol. 22, no. 7, pp. 507–509, 2010.
- [8] S. K. Dubey, T. Anna, C. Shakher, and D. S. Mehta, "Fingerprint detection using full-field swept-source optical coherence tomography," *Applied Physics Letters*, vol. 91, no. 18, p. 181106, 2007.
- [9] S. K. Dubey, D. S. Mehta, A. Anand, and C. Shakher, "Simultaneous topography and tomography of latent fingerprints using full-field swept-source optical coherence tomography," *Journal of Optics A: Pure and Applied Optics*, vol. 10, no. 1, p. 015307, 2008.
- [10] E. Auksoorus and A. C. Boccara, "Fingerprint imaging from the inside of a finger with full-field optical coherence tomography," *Biomedical optics express*, vol. 6, no. 11, pp. 4465–4471, 2015.
- [11] L. N. Darlow and J. Connan, "Efficient internal and surface fingerprint extraction and blending using optical coherence tomography," *Applied optics*, vol. 54, no. 31, pp. 9258–9268, 2015.
- [12] R. Breithaupt, C. Sousedik, and S. Meissner, "Full fingerprint scanner using optical coherence tomography," in *Biometrics and Forensics (IWF), 2015 International Workshop on*. IEEE, 2015, pp. 1–6.
- [13] J. Aum, J.-H. Kim, and J. Jeong, "Live acquisition of internal fingerprint with automated detection of subsurface layers using OCT," *IEEE Photonics Technology Letters*, vol. 28, no. 2, pp. 163–166, 2016.
- [14] M. Liu and T. Buma, "Biometric mapping of fingertip eccrine glands with optical coherence tomography," *IEEE Photonics Technology Letters*, vol. 22, no. 22, pp. 1677–1679, 2010.
- [15] D. Cui, X. Liu, J. Zhang, X. Yu, S. Ding, Y. Luo, J. Gu, P. Shum, and L. Liu, "Dual spectrometer system with spectral compounding for $1\text{-}\mu\text{m}$ optical coherence tomography in vivo," *Optics letters*, vol. 39, no. 23, pp. 6727–6730, 2014.
- [16] L. Liu, N. Chen, and C. Sheppard, "Double-reflection polygon mirror for high-speed optical coherence microscopy," *Optics letters*, vol. 32, no. 24, pp. 3528–3530, 2007.