Mobile Touchless Fingerprint Acquisition And Enhancement System

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***Abstract*—This study is concerned with the identification of individuals by using finger images captured by mobile devices. Within the scope of this study, the problems encountered in obtaining a fingerprint with mobile devices are initially determined and an apparatus is designed to solve and handle these problems. In order to analyze the feasibility, test the proposed apparatus and enhancement approach, the finger images captured by the mobile device are compared with the fingerprints collected by the sensor. The proposed approach is tested in the database composed of 104 fingerprints images captured from 52 different individuals. It has been seen that the fingerprints collected by the optical sensor are matched to the fingerprints captured by the apparatus integrated with the mobile device. The overall results of the proposed approach show performance with a FAR of 0.05% and FRR of 0.54% by using the apparatus designed.**

***Index Terms*—Fingerprint, touchless, mobile, enhancement, feature extraction, CLAHE, STFT.**

I. INTRODUCTION

Fingerprint image acquisition is considered as the most critical step of the automatic fingerprint authentication system because it determines fingerprint image quality, which has serious impacts on overall system performance. The classification and recognition mechanisms developed by using the uniqueness of fingerprinting are widely used in forensic science to support criminal investigations, and to establish high-security platforms in authentication systems and commercial applications. In the past, fingerprints were collected by ink technique in law enforcement while the fingerprints used in civil and criminal AFIS (Automatic Fingerprint Identification System) are collected using electronic devices on which the finger surface is directly sensed [1]. The general procedure for capturing a fingerprint is to register mark by placing the finger on the platen of a live-scan device or pressing the finger on a flat paper after the ink is applied to the finger. Since the fingerprint surface is not flat, the finger must be pressed on the sensing paper or plate of the device when the image is taken with the device or ink to obtain sufficient reference points from the fingerprint and to examine a large area [2]. Mentioned approaches are called touch-based fingerprint collection methods. Touch-based fingerprint acquisition mechanisms cannot overcome these problems: (i) deformation due to degradation of the elastic structure of the fingerprint under pressure, (ii) deformation caused by excessive dryness, humidity or wet surface of the finger, (iii) skin deformations such as cuts and wounds on the finger surface, (iv) contamination caused by residual prints on the sensor or scanner platen, (v) noise caused by sensor, (vi) inability to place the finger in the correct position on the sensor surface, (vii) the cost of the device and decreasing durability due to intensive use of the device [2]–[7].

Because of the problems mentioned in the data collected by the touch-based methods, new approaches have been proposed in which fingerprint can be collected without touch. The approaches used to capture a fingerprint-based on touchless technology can be divided into two main groups: Reflection-based Touchless Finger Imaging (RTFI) and Transmission-based Touchless Finger Imaging (TTFI) [8]. Ultrasound sensors have been developed with TTFI approach. However, the preferability of this approach is low due to the size of the device used for image acquisition, the cost of manufacturing the device, and the long fingerprint acquisition time [2]. Fingerprint collection methods using a digital camera, 2D and 3D scanners are evaluated in RTFI approach.

The fingerprints collected using touchless approaches are presented as a solution to the problems arising from the collection process by touch-based approaches mentioned above. However, the use of these devices has brought about different problems. These are classified as: (i) low contrast between the ridge and the valley pattern, (ii) background noise, (iii) non-uniform lighting, (iv) depth of field issue, (v) motion blur and defocus [2]–[7].

Nowadays, most of the smartphones are equipped with colored cameras that have the high processing power and high-quality resolution, zoom, and auto-focus [9]. For this reason, a mobile device camera was used in this study considering the features mentioned as well as ease of use and cost-effectiveness. In order to eliminate the weaknesses caused by the use of touchless methods, fingerprints were collected with an apparatus attached to the mobile device. An approach for improving these fingerprints collected with the mobile device has been proposed in this study. The proposed approach has been designed in a flexible manner that allows fingerprints collected using the mobile device to be compared with each other as well as comparing fingerprints collected with the mobile device and the sensor. Therefore, the proposed approach is an alternative to touchless fingerprint acquisition methods and provides an infrastructure for accelerating the identification

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process in terms of matching fingerprint collected by touch-based and touchless methods in critical areas such as crime scene investigation.

In section II, studies on acquisition, enhancement, and matching of the fingerprint using touchless methods are examined. In section III, the proposed fingerprint acquisition and enhancement stages are explained. Criteria determined during data acquisition stage, techniques and methods used in the enhancement stage are introduced in detail. In order to verify the validity and quality of the fingerprint collected, the characteristics of the fingerprints collected by the sensor and fingerprints collected by the proposed approach are compared and the results obtained are shared in section IV. In section V, general evaluations of the study are given.

II. RELATED WORKS

Fingerprint biometry has been studied in depth from a different perspectives and has been used in many different disciplines together [10]. The current development of mobile devices and the increase in usage have brought new ideas to the use of this technology in combination with biometric systems. In particular, cameras, which are now the most essential feature of mobile devices, have gained importance due to usability for different purposes. Based on this situation, studies in the literature on image acquisition/ enhancement/ matching using mobile devices were examined and the results obtained are introduced in Table 1 [3], [11]–[21]. The summary of the studies in the literature is given under the following headings:

- The length of the wavelength of the light source from which the fingerprint is imaged affects the visibility of the fingerprint. Since the light sources having long wavelengths have the ability to penetrate the skin and they are absorbed by the epidermis, the ridge lines become more prominent. Therefore, long-wavelength light sources are used in most of the studies in the literature.
- Variation in the distance between the finger and the camera causes many problems such as defocus and blurring. For this reason, in most studies in the literature, fingerprint images are obtained by fixing the distance or some solutions are developed by image scaling.
- The curvature of the fingerprint structure leads to regional contrast differences in the fingerprint image. To overcome this problem, the image is taken in three dimensions. Three-dimensional images are obtained by combining images obtained from photometers, SFDs or multiple cameras that display the finger from different angles.
- The value of the resolution and depth of field of the camera used directly affects the image quality of the collected fingerprint. For this purpose, professional devices or standard devices, which are used together with macro lenses, are used to obtain high-quality images.
- In case where the data acquisition medium is not standard for two-dimensional images obtained with mobile devices, web cameras or digital cameras, several processing steps are performed to develop fingerprints. Particularly in the segmentation step, it is seen that the process of separating fingerprint from the other objects in the environment is very difficult.

III. PROPOSED APPROACH

The proposed approach aims at the acquisition of fingerprint captured using a mobile device and their enhancement in an appropriate way. Our approach is based on touchless fingerprint acquisition. An apparatus is used to standardize the environment where the fingerprint is collected and to increase the success rate of data acquisition /enhancement steps. After that, image enhancement steps are used to make fingerprints appropriate for feature extraction. All processing steps are summarized in Figure 1 and the techniques and methods used are explained in the subsections below.

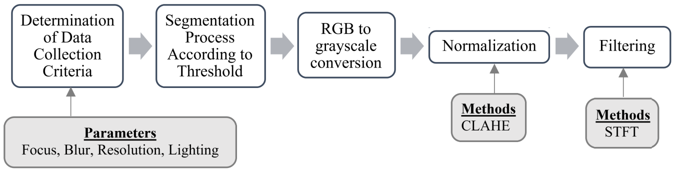
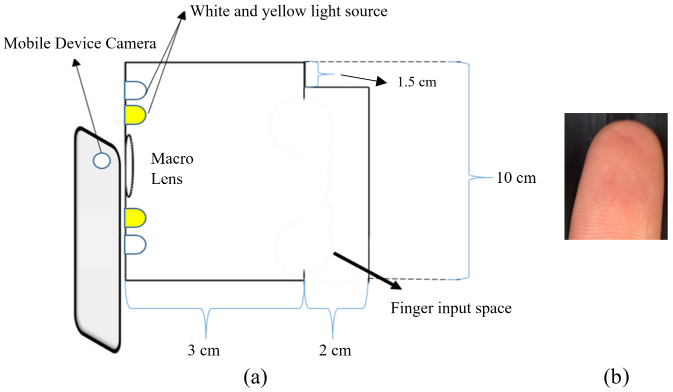


Fig. 1. Proposed Approach Steps

A. Touchless Fingerprint Capture Process

The steps to be applied to the collected fingerprint vary depending on the surface or background on which it is displayed. For finger images with a complex background, pre-processing applied to separate the finger from the image becomes more demanding. In addition, parameters such as light source used to illuminate the box while the image is taken, illumination ratio, light intensity and wavelength, resolution of the mobile device used in imaging, distance of the device to the finger directly affect the collected fingerprint data. In order to eliminate the constraints in obtaining fingerprints with the mobile device and to use the finger image collected with the mobile device in recognition systems, an apparatus for obtaining the finger images with the mobile device has been developed in maximum quality.



(a) (b)

Fig. 2. Schema of the used acquisition apparatus (a), finger image collected by apparatus (b)

TABLE I
EXAMINATION OF EXISTING STUDIES WHICH USE TOUCHLESS METHODS FOR ACQUISITION OF FINGERPRINTS

Ref.	Used Device	Main Purpose	Used Methods	Problems	Medium Conditions	Finger-camera distance	Resol. (Mp)	Macro External/	Feature Internal	Light Source	Database	Success Rate
[3]	Canon PowerShot Pro1	Core point detection	Skin color detection algorithm, STFT, core point detection algorithm	Focus, depth of field, light	Standard	Fixed	8	-	+	Led	-	95.44% accuracy for core point detection
[11]	Nexus S, Galaxy Nexus	Authentication	Sobel filter, finger detection and rotation algorithm, median filter, feature extraction with FingerJetFX	Segmentation, finger detection, orientation angle	Not standard	Not fixed	5	-	+	Led	41 pers. 1494 fingerprints	EER: 19.1%
[12]	Canon PowerShot Pro1	Authentication	Skin color detection algorithm, STFT, core point detection algorithm, Gabor feature extraction, PCA	Focus, blur, light, depth of field, data size	Standard	Fixed	8	-	+	Led	103 pers. 1030 fingerprints	EER: 5.63%
[13]	Iphone 5s	Authentication	Median filter, Histogram equalization, Gaussian filter, Scatnet	Environmental illumination and background	Not standard	Not fixed	8	-	-	Flash	64 pers. 5100 fingerprints	EER 3-10%
[14]	Iphone 4, Galaxy S1 and N8	Authentication	Wiener filter, Gauss filter, CNS, PCC, Magnitude of the Fourier spectrum, wavelet transform, MINDTCT, BOZORTH3	Resolution, Rotation, Scaling, Segmentation	Not standard	Not fixed	5-13	-	-	Not used	25 pers. 1800 fingerprints	EER: 3.74%
[15]	PDA device	Appropriate fingerprint image selection	Focus measurement algorithm, Half Gabor filter	Segmentation, focusing, rotation	Not standard	Not fixed	N/A	-	-	N/A	15 pers.	EER: 3.02%
[16]	N95, HTC Desire	Authentication	Verifinger 6.0 Extended SDK	Focus, resolution, distance	Standard	Fixed	5	-	+	Flash	22 pers. 1320 fingerprints	EER: 4.5%
[17]	Nexus S, Galaxy Nexus	Authentication	Segmentation, skin color detection, scaling, image cropping, MorphoLite SDK	Light, segmentation	Not standard	Not fixed	5	-	-	Not used	37 pers. 990 fingerprints	EER: 3.0% FAR:0.1%, FRR:2.7-6.7%
[18]	Xiaomi Redmi Note 3 Pro	Authentication	Skin color detection, Monogenic wavelet based PC, VeriFinger SDK	Light, distance, resolution	Not standard	Not fixed	16	-	-	Flash	50 pers. 200 fingerprints	EER:7.4%
[19]	N/A	Authentication	Adaptive threshold, PCA, ADhist, SURF	Light	Not standard	Not fixed	N/A	-	+	Flash	50 pers. 150 fingerprints	EER: 3.33%
[20]	N/A	Touch-based/less methods comparison	CLAHE, Gabor filter, Source AFIS	Segmentation, rotation	Not standard	Not fixed	16	-	-	Flash	-	EER:6-15%
[21]	Web Camera	Authentication	Gamma correction, directional fourier filter, NFIQ algorithm	Light, segmentation	Not standard	Fixed	N/A	-	-	Led	6 pers. 400 fingerprints	FAR:0.18% FRR:10.29%
Prop.	Iphone 6s	Touch-based/less methods comparison	Segmentation with threshold, CLAHE, STFT filter, SourceAFIS	-	Standard	Fixed	12	+	-	Led	52 pers. 104 fingerprints	FAR:0.05% FRR:0.54%

When designing the specified apparatus:

- The first factor is lighting. The finger surface is illuminated by light sources of different frequency values. However, it was seen that parameters such as light intensity and angle directly affect the visibility of ridge lines of finger. Therefore, a dark box mechanism has been designed to eliminate the variability of these parameters associated with the light source affecting the data acquisition. In this dark box, the source sends light at the correct angle and intensity towards the finger. Reflected lights can be seen more clearly due to the darkness of the environment and the finger image is obtained in good quality.
- A macro lens is used to eliminate the variability in image quality obtained using the mobile device. In this way, an approach that can be used with low-resolution mobile devices is presented.
- The distance at which the used macro lens clearly shows the ridge lines of finger are measured and the length of the dark box is adjusted taking this distance into account.
- The area where the finger is placed in the dark box is designed to scale the finger from left and right. Thus, individuals cannot move their fingers to the right or left. For this reason, problems such as lack of reference point of the displayed part of the finger, blur and defocus due to shaking or motion of the finger are removed by the designed apparatus.
- The low contrast between the ridge lines, which is an important problem in touchless acquisition methods, is minimized as much as possible with the proposed apparatus.

In the apparatus seen in Figure 2a, white and yellow light sources having two different wavelengths, are used. The width of the dark box is determined by the distance at which the macro lens can display the finger most clearly. It has been seen that when the finger is illuminated with a single source or is illuminated very intensely, the image of the finger disappears in the portion corresponding to the position where the illumination occurs. Therefore, light sources having more than one medium intensity is placed in a circular manner in the interior of the apparatus developed. In this way, data loss in fingerprints is prevented. Finally, in order to eliminate the problems caused by the placement of an individual's finger at an incorrect angle or position, appropriate curves to guide the placement of the finger have been added to the apparatus. The finger image displayed by the apparatus developed by taking these criteria into consideration is shown in Figure 2b.

B. Enhancement of Fingerprint Collected by Touchless Method

Image enhancement is a process that increases the interpretability of pixels to extract meaningful information from image in decision mechanisms [22], [23]. It is aimed to eliminate the factors that affect image quality in the enhancement stage applied after the data collection. In the image enhancement, the methods to make clear ridge lines, fill gaps, improve image contrast, reduce data size and noise are applied [24], [25]. Fingerprint images are collected from the individual by touchless methods with the help of the apparatus developed within the scope of the study. The sequence of enhancement steps to be applied to these images and the methods used in these steps differ with the enhancement steps applied to the fingerprints collected by touch-based methods [3], [12]. However, the quality of the fingerprint image collected using the mobile device is influenced by factors such as variability of light and background region, resolution, bit and depth of field. The techniques and methods used in the enhancement stages are designed to solve these problems. These stages applied to the fingerprint images obtained with the designed apparatus to eliminate all these problems are explained below.

1) Segmentation: Segmentation methods are divided into three: pixel-based, block-based and graph-based [26]. In pixel-based approaches, the entire process is performed one by one for each pixel that forms the building block of the image. To calculate the density values of the pixels of the image, a result is produced by analyzing the neighbor pixels corresponding to a particular matrix, rectangular or a square block. Pixel-based image segmentation algorithms tend to determine whether each pixel of the image belongs to the foreground area or background area [26]–[28].

Segmentation is very important for data collected by mobile devices. When mobile devices are used during fingerprint acquisition, the background information of the finger is also collected. The data extraction process is performed using a series of segmentation methods to separate fingerprint data from the background. However, not all background data can be cleared and this leads to incorrect reference points. When the studies on fingerprints collected in different environments using mobile devices are examined in the literature [3], [11]–[14], it is seen that being able to perform the segmentation stage correctly has a direct effect on the similarity rate.

Thanks to the apparatus developed within the scope of this study, it is ensured that there is no other object other than a finger in the image as the background region is fixed. Otherwise, these objects would have to be extracted from the image, which would lead to a prolongation of the image analysis process. In this study, the color of the background region was determined as the black. Thus, it was aimed to easily determine skin color. The color black has the lowest pixel value corresponding to 0 in gray-level images and RGB(0, 0, 0) in color images. Therefore, the skin color value can be readily distinguished from the background region, even if images are illuminated by white or yellow light sources. In this study, the segmentation stage was performed with a single comparison parameter (T=100). This eliminates changes in color pixels due to the reflection of light, the background of the image becomes completely black, and the finger is separated from the background. If the color changes in the background region that are dependent on light are not fixed, the filtering step results in the improvement of objects other than the finger. Therefore, incorrect feature extraction can occur.

2) Normalization: The algorithms that detect fingerprint minutiae points are directly affected by the quality of the

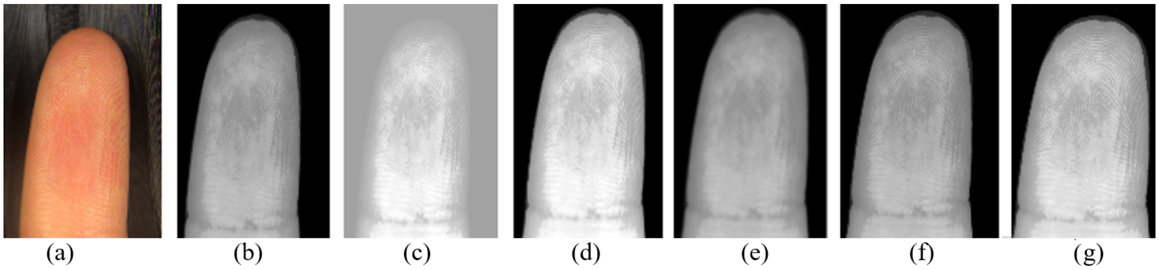


Fig. 3. Applying normalization methods to finger image collected by apparatus, Raw input image (a) Median filtering (b) Histogram equalization (c) Contrast stretching (d) Gaussian filtering (e) Wiener filtering (f) Hong-Normalization method (g)

collected finger image. In an ideal finger image, ridge and valley lines vary and flow in a fixed orientation. The ridge and valley lines from finger images collected under appropriate conditions can be easily identified and the minutiae points can be correctly detected. In general, there are several types of distortion situations associated with fingerprint images: (i) small gaps between the ridge lines, (ii) deterioration of the parallelism property due to the noise between the valley and the ridge lines, (iii) cuts, wrinkles, etc. on finger surface.

In this study, techniques and methods used for fingerprint normalization have been examined in detail. As a result, contrast stretching, histogram manipulation, Hong normalization [29] and Wiener filtering [30] were used as the initial processing steps for a sophisticated fingerprint enhancement process. In most of the studies examined, instead of using only one normalization method, different combinations of the above methods were applied consecutively and more successful results were obtained. In fact, the normalization method to be used should be selected according to the data on which the method is applied. For instance, the histogram equalization method is one of the most preferred approaches for mobile fingerprint images, as it is successful in increasing the sharpness of low contrast images [20]. The normalization methods mentioned above are applied to fingerprints collected via the developed apparatus and the results are given in Figure 3.

The histogram equalization method makes improvements based on the overall contrast of the image. However, this makes it difficult to extract some points especially in detail images. In order to solve this problem, Pizer developed a method called CLAHE [31]. This method, which is basically a histogram equalization approach, improves image noise on a block basis [32]. Since this method is applied on a gray-level image, the image in RGB format must first be converted to gray level. The original image is then split into blocks so that they do not collide with each other and histogram equalization is applied to these blocks. As a result of the histogram equalization applied to the blocks, the noise ratio in the image increases. In order to overcome this problem, contrast limitation is made [31]–[33].

After the cropped pixels are distributed equally to the other blocks, linear interpolation method is applied to remove these regions. In the separated blocks, the average value of the pixels, each equalized to the gray value, is calculated with Eq.1. In this equation, N_{gray} is the number of gray levels in the block, N_{CR-Xp} the number of pixels on the x axis, and N_{CR-Yp} is the number of pixels on the y axis.

$$N_{aver} = \frac{(N_{CR-Xp} x N_{CR-Yp})}{N_{gray}} \tag{1}$$

Then, Eq. 2 determines the contrast limit by multiplying the average value of the pixels in the block and the maximum of the average pixels at each gray level.

$$N_{CL} = N_{clip} x N_{aver} \tag{2}$$

More information on the steps of the CLAHE method used in this study can be found in [33]. The output of the fingerprint collected using the proposed approach is improved by the CLAHE method and it is shown in Figure 4.

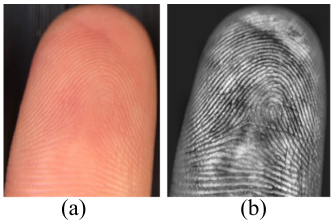


Fig. 4. Input image (a), Normalization with CLAHE (b)

3) Filtering: Fingerprint consists of orientational and non-stationary signals [34]. These structures need to be enhancement by maintaining the continuity of the ridge line. The filtering method, which can be applied in both spatial and frequency domains, is performed depending on the orientation and frequency estimation. Since the filtering in spatial domain results in computational complexity due to convulsions, filtering is performed in the frequency domain. Therefore, the image is transformed into the frequency domain by Fourier transform [35]. The features such as orientation and frequency information are extracted from this image. Using this information, the filtering function in the frequency domain is applied to the image. Within the scope of this study, it is emphasized whether the whole image can be analyzed or not depending on the function used to convert to frequency domain.

Time and frequency analysis are required to analyze non-stationary signals such as fingerprints. In the literature, STFT has been proposed to perform time and frequency analysis of such signals. With this approach, when the fingerprint are analyzed, it is seen that the information such as direction and frequency are obtained more reliably and the success of the filtering stage increases as well [34]. For this reason, it is considered that STFT should be applied to finger images collected with the developed apparatus.

$$X(\tau_1,\tau_2,\omega_1,\omega_2) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} I(x,y)W^*(x-\tau_1,y - \tau_2)e^{-j(\omega_1 x+\omega_2 y)}dxdy \tag{3}$$

The time-frequency analysis of the finger images is performed as in Eq. 3. In this equation, the image to be analyzed I(x,y), the window function W, the spatial frequency parameters ω_1 and ω_2 , the time parameter τ_1 and τ_1, time frequency atoms $X(\tau_1,\tau_2,\omega_1,\omega_2)$ are represented. After the image is converted to frequency domain, the filtering is applied by extracting information such as orientation and frequency from the image. More information on the filtering with STFT method used can be found in this study [34]. In Figure 5, the result of the finger image collected by the developed apparatus after the application of STFT is shown.

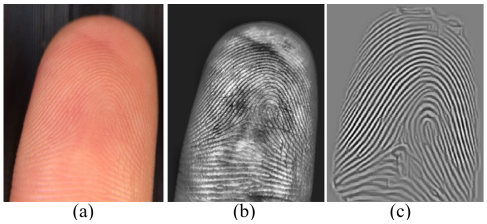

(a) (b) (c)

Fig. 5. Input image (a), Normalization with CLAHE (b) STFT transform (c)

IV. EXPERIMENTAL RESULTS

The apparatus setup and parameters, dataset employed for the experimentation, verification methods, experimental results and the dataset employed for the experimentation are explained below.

The used setup composed of a IPhone 6s, developed apparatus and a yellow LED illumination is shown in Figure 2. The distance from the camera to the fingerprint is 6 cm, the distance from the macro lens to the box surface where the finger is placed is 5 cm. The leds were placed at a distance 5 cm to the box surface where the finger was placed and inclined with an angle $\theta = 90°$ with respect to the mobile device. A macro lens with 10 cm focal length was used in order to capture high quality image. The size of the captured images is $wxh = 2097x2417$ pixels and resolution of image is 12 megapixel.

In order to test the validity of the proposed approach, 52 different fingerprints were collected from 52 different individuals by using both the sensor and the developed apparatus. Each fingerprint was captured separately 2 times, for a total of 104 images. The mobile device used to collect the fingerprint data set was Iphone 6s and the optical sensor was the Papillon DS-21s. All the enhancement processes performed were developed in Matlab 2018b on the Windows10 operating system along with a core i7 processor and 16 gb ram as the hardware configuration.

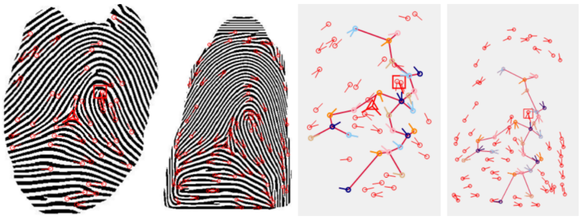


Fig. 6. Comparison of fingerprints collected with proposed apparatus and sensor

The fingerprint collected using the proposed apparatus was compared with the fingerprint collected using the sensor to determine whether the qualification of the fingerprint collected and the enhancement applied were sufficient for biometric identification. The matching minutiae points obtained from this comparison are shown in Figure 6. The similarity of the data collected by two different methods was tested with Neurotechnology, Verifinger 6.0 Extended SDK and the matching was successfully completed by finding 90 and above minutiae points of the compared fingerprints. This shows that the collected fingerprint has enough distinctive characteristic data for a biometric identification process.

Since similarity scores are calculated between two samples, fingerprints are collected as P samples from each of Q individuals. A genuine score can be defined as a similarity rate between two samples from the same individuals, and an impostor score can be defined as a similarity rate between two samples from different individuals. The equations used for calculating genuine and impostor scores are given in Eq. 4 and Eq. 5.

$$Score_g = Qx\frac{P!}{(P-2)!\,2!} \tag{4}$$

$$Score_i = p^2x\frac{Q!}{(Q-2)!\,2!} \tag{5}$$

The false recognition rate (FRR) and the false acceptance rate (FAR) are measures of the likelihood of incorrect rejection and incorrect acceptance respectively. FAR and FRR are obtained by calculating the values of true accepted (TA), false accepted (FA), false rejected (FR) and true rejected (TR), which are formed depending on the acceptance or rejection of any two fingerprint comparison results. Also, these values are obtained by calculating the genuine and imposter scores.

$$FAR = \frac{FA}{FA+TR} \tag{6}$$

$$FRR = \frac{FR}{FR+TA} \tag{7}$$

According to genuine score and impostor score, FAR and FRR are calculated using Eq.6 and Eq. 7, and evaluation results are presented in Table 2.

TABLE II
EVALUATION RESULTS OF PROPOSED APPROACH

	Mobile-Mobile	Mobile-Sensor
FAR	0.01%	0.05%
FRR	0.03%	0.54%

V. CONCLUSIONS

In this study, touchless and touch-based acquisition techniques were compared. The problems encountered in capturing a finger image with the touchless methods were identified and an apparatus was proposed to eliminate these problems. In order to test the proposed apparatus and enhancement approach, the finger image collected by the mobile device were compared with the fingerprints collected by the sensor. The proposed approach was tested in the database of 104 fingerprints images captured from 52 different individuals. The proposed approach shows that the fingerprints collected by the sensor are matched to the finger image collected by the apparatus integrated with the mobile devices. It has been seen that mobile devices can be used for identification instead of sensors or scanners. The system, which is composed of designed apparatus and proposed approach, offers cost-efficient identification/verification mechanism.

With the advancing technology, the function of the cameras used in mobile devices shall be able to increase and the quality of the fingerprint collected using these devices will increase. As the image quality increases, the ridge and valley lines of the finger image will become more pronounced, and feature extraction will be easier. The study is especially expected to shed light on future studies on the matching of the latent fingerprints detected at the crime scene and the fingerprints of suspects collected using the proposed approach. In addition, most fingerprint acquisition methods are designed to collect data from living individuals. It is predicted that fingerprints can also be collected from cadavers with the proposed approach.

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