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Fingerprint preprocessing using FCN and U-net methods

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Abstract

This paper analyzes the importance of optimizing fingerprint images from the perspective of front-line forensics personnel. Due to defects such as fingerprint ridge blurring and fingerprint image overlap, it may cause delays in fingerprint identification and lead to misjudgments (false positives, false negatives) and other consequences. This paper simulated common fingerprint images (fuzzy feature points) at criminal cases, and captured, segmented, and reconstructed fingerprints. Two deep learning model architectures, U-net [1] and FCN [2], were applied to realize image segmentation and image reconstruction. The first task is fingerprint image segmentation, where the fused images are segmented into incomplete fingerprints. The second task is to reconstruct the complete fingerprint from the image obtained after segmenting the incomplete fingerprint. Field verification for fingerprint image reconstruction and separation on red envelope were carried out. Ethyl cyanoacrylate method is used to visualize paper latent fingerprints and would produce "white" fingerprints, which is not easily distinguished from the red background. The pre-processing of fingerprints on red paper background is the key to the accuracy of fingerprint recognition. U-net image processing technology demonstrates the contributions of the forensic personnel in processing fingerprint images are as follows: [1] Improve efficiency. [2] Reduce misjudgment.

Subject Classification: *30D20.*

Keywords: *Deep learning, U-net, Image segmentation, Image reconstruction.*

1. Introduction

Fingerprint is one of the main biometric features because of its uniqueness, acceptability and low cost [3]. From the review of literature, the purpose of fingerprint image segmentation is to separate the fingerprint friction ridges from the fingerprint image. This is one of the determinants of the performance of the Automated Fingerprint Identification System (AFIS) [4]. Partially defective fingerprint images often appear in identity authentication due to reasons such as fingerprint surface damage, fingerprint surface contamination or fingerprint sensor damage or contamination etc. [5]. Recovery of fingerprints is challenging and especially when there are multiple fingerprints overlap. Experts usually examine overlapping fingerprint images by manually distinguishing ridges to separate fingerprint images. This manual method is extremely inefficient and prone to making errors [6]. Latent fingerprints are usually ambiguous and captured only a small finger area with large non-linear distortions [7]. From a report analyzing 209 detected residential theft cases in the UK, it was found that about 77% of the cases were solved by arresting the suspect immediately after the incident and had clear testimony from witnesses. There were only 10% of the cases were solved based on police investigations. Moreover, the proportion of resources devoted to the investigation of residential burglary cases was quite low accounted for only about 7% of all police activities [8]. Serial house theft criminals are mostly experienced veterans or experts. It does not take too much effort and time to complete a crime and there are usually protective measures in which few clues or forensic evidences are left on the scene [9]. From August 17th to 23rd in year 2012, the research team investigated five consecutive residential burglaries including Yang O Xiang in Jiali District, Tainan City, Taiwan. After analyzing the fingerprints left by the suspects at the scene and the fingerprints collected at the crime scenes of the 4 house burglaries of Chen O Zhu and others that occurred in this area between February and March of the same year, the fingerprints were sent to the forensics for comparison from the fingerprint database and no match was found. In Addition, from January to April 2013, Wang O Min with other 5-person theft group who fled and were pursuit in Jiali District, Tainan City, Taiwan was suspected of consecutive residential intrusions involving a total of 49 theft cases [10]. After analysis, it was found that Wang O Min and other members of the theft group were all based in Kaohsiung City. In order to avoid police pursuit, the group deliberately chose Sunday morning hours (At the time, most of the victims will choose to travel with their families on holidays so the protection of the house is the lowest) and drove from Kaohsiung City to Tainan City to commit the crime. They would hide the vehicle and stole the motorcycle to evade police investigation to avoid being tracked down. The theft group also found similar shoe prints in the forensic analysis from the above-mentioned 7 cases of house intrusion crime scene. In the end, the research team cooperated with the special case team to map the criminal pathway of Wang O Min theft group. While reviewing the surveillance cameras installed by the victims, it was found that the suspect Wang got off the motorcycle to wipe the handlebars when discarded the stolen motorcycle. As the result, the research team finally collected the incomplete fingerprints and DNA tissue of the suspect Wang at the scene. The above cases show that the actual utility of physical evidence at the crime scene is not as useful as expected and has its limitations [11].

According to a research report of the British Home Office, materials evidence will have an obvious funnel (or Attrition) effect in the actual investigation process [12]. For example, the feedbacks of applying fingerprint after a residential burglary case include the case rate of sending personnel to collect fingerprints is about 59-89%, the fingerprint discovery rate is about 13-66%, the fingerprint confirmation rate (referring to the matching ratio of on-site fingerprints and archived fingerprints) is about 2-9% and the arrest utilization rate (referring to the on-site fingerprint is the fingerprint of the criminal) is about 0-9%. With the evolution of artificial intelligence (AI) technology, this kind of biometric technology will therefore last for a long time. The US Federal Bureau of Investigation (Fingerprint Identification Section) implemented the Next Generation identification (NGI) system in 2013 to fully update the department's fingerprint computer system and this update plan was continued until 2014. As the result, this NGI system not only expanded the original fingerprint image access capacity but more importantly increased the palm prints comparison identification function [13,14]. In the face of unsolved major crimes, the only remaining key to solve the case is to compare the fingerprint photos kept at the scene at that time.

NEC fingerprint workstations are commonly used in criminal forensic instruments. Its advantage is to improve the speed and accuracy of fingerprint comparison through the calculation between minutiae points (number of ridges). However, fingerprint minutiae such as ridge ending and bifurcation must be made manually and fingerprint images also need to be manually adjusted in order to make obvious contrast in different fingerprint ridges. By using Ninhydrin to display latent paper fingerprints will have purple intermittent ridges and it is necessary to manually draw the pattern to increase the probability of fingerprint matching. It is to say that the efficiency and accuracy of identification still need to be further enhanced.

Artificial intelligence is widely used in various fields (ie. smart manufacturing, financial services, medical imaging, and homeland security). For example, the Israel Counter-Terrorism Bureau has been a longtime sponsor of Dr. Champod and his team aimed at "proactive forensic science in biometrics" of forensic science at the Université de Lausanne, Lausanne, Switzerland [15]. It is to develop strategies, technologies and new materials against terrorists and criminals. Another example is that criminals commonly shown in movies use silicone materials to forge and alter the victim's fingerprints in order to deceive the fingerprint recognition system and hence causing serious losses. To this end, Dr. Champod's team has successfully developed the Presentation Attack Detection (PAD) system which has successfully resisted the invasion of forged and altered fingerprints [16].

This study uses the supervised learning method [17] to simulate fingerprints of senior forensics personnel and attribute the minutiae characteristics (such as bifurcation, ridge ending) of fingerprint images in labels. When there are more collected fingerprint data, the higher accuracy of characteristic labeling would result a better accuracy of its analysis. This experiment is focusing on fingerprint images of red envelope and plastic packaging bags by applying the methods such as segmentation and reconstruction in which the steps can be divided into image capture, image pre-processing, feature extraction, fingerprint feature comparison and reconstruction in order to construct a complete set of fingerprint identification system.

2. Related Works

2.1 *Fingerprint collection materials and processes*

For the red envelope made of a glossy film material that is water-resistant, we employ the ethyl cyanoacrylate method, applying heat and fumes until latent fingerprints become visible, typically appearing as white impressions. Subsequently, we enhance the fingerprints using fluorescent powder and capture photographs for comparative analysis.

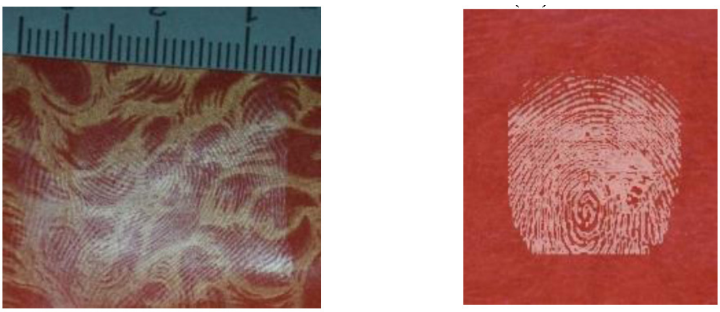
2.2 *Simulated fingerprint collection image*

The RGB sensor of the image is situated within the visible light spectrum, while the fingerprints on the red envelope are imperceptible to the human naked eye, necessitating the use of chemical dyes. The data collected from the fingerprint images of Africans were proposed by Shehu et al. [18] which contained 600 fingerprints of Africans. The fingerprints of 10 fingers of each person were collected that contributed a total of 6000 fingerprint images. This data can be further divided into three kinds of augmented fingerprint images of Easy (17,931), Medium (14,272) and Hard (14,272) according to different degrees of incompleteness. Augmentation included the methods of partial obliteration, partial center rotation and partial z-cut. In this study, only 1000 incomplete fingerprint images of the Easy level were used to synthesize red envelope images which were called fusion image. The synthesized image was used to simulate the red envelope fingerprints collected at the crime scene. We divided the fused images into a training set and a test set with 800 and 200 images respectively.

2.3 *Labeling*

Given the complexity and high cost associated with fingerprint collection technology for crime scene red envelopes, it is essential to adhere to the procedural steps outlined in section 2.1. Fingerprint collection may encounter challenges related to insufficient samples or issues concerning personal data laws. To ensure the feasibility of this research study, we opted for image simulation to replicate real-world fingerprint collection scenarios. In this study, Dr. Pan was engaged to annotate the simulated images and assess their authenticity in comparison to actual collected fingerprints. The comparative results from Figure 1 distinctly reveal a high degree of resemblance between our simulated fingerprints and those collected from real crime scenes. This similarity will significantly enhance the subsequent model validation process.

Figure 1 (a) is the fingerprint sampled in the real world. The background is the red envelope with bright film material, and the fingerprint is revealed through the ethyl cyanoacrylate method. Figure 1 (b) is the image generated by simulating Figure 1 (a).



(a) True sampling (b) Simulated sampling

Figure 1

Images of real sampling and simulated fingerprint appearing on red envelope.

2.4 *Models*

2.4.1 Fully convolutional network (FCN)

The fully convolutional network (FCN) is a deep learning architecture wWidely applied in the field of computer vision, specifically designed to address tasks such as segmentation, recognition, and localization. Compared to traditional Convolutional Neural Networks (CNNs), the main innovation of FCN lies in completely discarding fully connected layers and replacing them with convolutional layers. This enables end-to-end processing of input images and allows for the output of feature maps with the same dimensions as the input image.

2.4.2 U-net

The U-net architecture was initially introduced in 2015 with the purpose of designing it for biomedical image segmentation, especially in tasks such as cell and tissue segmentation in microscopy images. The core of the U-net model lies in its ability to acquire different features through the use of an encoder, composed of convolution and pooling layers. Subsequently, these features are mapped back to the original spatial dimensions through a decoder. To effectively combine multi-scale features, the U-net incorporates a concatenation process by directly linking corresponding feature layers between the encoder and decoder.

3. Proposed Methods

The purpose of this research is to separate the fingerprint from the background of the red envelope, and then reconstruct the mask image of the fingerprint, and finally obtain a complete fingerprint image. The experimental process is shown in Figure 2. The input image is the fingerprint image with the red envelope background. After the fingerprint segmentation, the fingerprint mask image (segmentation result) is obtained, and then the fingerprint reconstruction is performed to obtain the reconstructed complete fingerprint (reconstruction result).

It is mainly divided into two stages such as segmentation and reconstruction. The first stage of image segmentation is to use the thermal image invoices displayed by fingerprints collected by ethyl cyanoacrylate method and use U-net for fingerprint segmentation. The second stage is to reconstruct the incomplete fingerprint image after segmentation to obtain a complete fingerprint which is convenient for subsequent fingerprint characteristics extraction, comparison or recognition applications.

The purpose of this research is applying fused images to perform two different tasks of image segmentation and image reconstruction. These tasks are implementing the images in a cascade manner in order to obtain

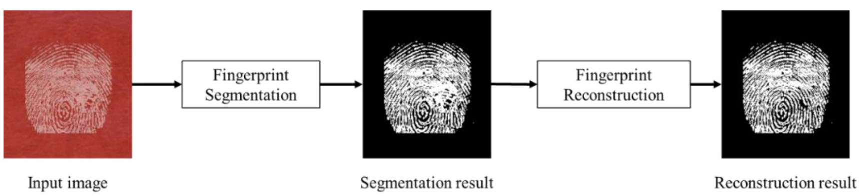


Figure 2

Fingerprint segmentation and reconstruction process.

a complete fingerprint image after reconstruction. Image segmentation and image reconstruction are operations based on image encoding and decoding. We use two different model architectures such as U-net and FCN to achieve image segmentation and image reconstruction. The first task is image segmentation where the fused images are segmented into incomplete fingerprints. The second task is to reconstruct the complete fingerprint from the image obtained after segmenting the incomplete fingerprint. Therefore, the overall goal is to segment and reconstruct the incomplete fingerprint image of the red envelope to obtain a complete fingerprint in order to facilitate subsequent fingerprint feature comparison and identification applications. In order to illustrate the feasibility of the method, the research method uses two different models such as U-net and FCN to predict and compare various depth layer parameters. Figure 3 and Figure 4 are the model architectures of U-net and FCN respectively. We can find that these two architectures are built on encoding and decoding operation processes where U-net has one additional concatenate feature link than FCN. The diagram is presented by Input is the input image, output is the output image, Conv is the convolution layer, MaxPooling is the maximum pooling layer, D-Conv is the deconvolution layer, the black arrow is the direction of the output result of the Layer and the red arrow Concatenate is used to link the output of a Layer to the output of another Layer.

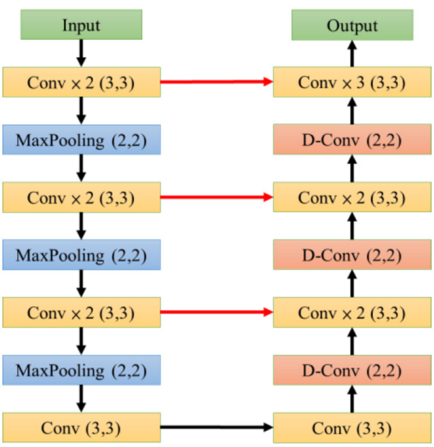


Figure 3

U-net model architecture diagram

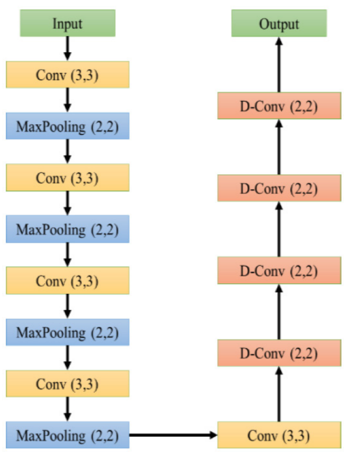


Figure 4

FCN model architecture diagram

4. Experimental Result

We use five different evaluation indicators include Accuracy, Jaccard Index (JI), Dice Similarity Coefficient (DSC), Sensitivity and Specificity in order to effectively evaluate the performance of the U-net and FCN models in the segmentation task with Eq. (1)-(5) such as *TP*, *FP*, *TN*, and *FN* are respectively expressed as True Positive, False Positive, True Negative and False Negative. The result of evaluation after fingerprint reconstruction is calculated by Mean Square Error (MSE) and Mean Absolute Error (MAE) that as shown in Eq. (6)-(7) where n is the number of pixels, y_i is the i pixel value of the Ground Truth position, y_i^p is the pixel value of predicted result position.

$$\text{Accuracy} = \frac{TP+TN}{TP+FP+TN+FN} \tag{1}$$

$$JI = \frac{TP}{TP+FP+TN} \tag{2}$$

$$DSC = \frac{2\times TP}{FP+2\times TP+FN} \tag{3}$$

$$\text{Sensitivity} = \frac{TP}{TP+FN} \tag{4}$$

$$\text{Specificity} = \frac{TN}{FP+TN} \tag{5}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - y_i^p)^2 \tag{6}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - y_i^p\right| \tag{7}$$

The results of image segmentation of incomplete fingerprints of red envelope by using U-net and FCN models in various depths in Table 1. The segmentation results of the U-net model with depth 6 are better than the other five methods.

Table 1

Segmentation Performances of testing datasets for the proposed U-net and FCN.

Models	**U-net**			**FCN**		
Depth	**4**	**5**	**6**	**4**	**5**	**6**
Accuracy	0.9952 (0.0014)	0.9946 (0.0017)	**0.9956 (0.0013)**	0.9633 (0.0119)	0.9661 (0.0109)	0.9617 (0.0120)
JI	0.9929 (0.0021)	0.9920 (0.0025)	**0.9936 (0.0019)**	0.9494 (0.0156)	0.9524 (0.0149)	0.9469 (0.0161)
DSC	0.9399 (0.0119)	0.9398 (0.0119)	**0.9399 (0.0119)**	0.9387 (0.0122)	0.9386 (0.0122)	0.9386 (0.0122)
Sensitivity	0.9958 (0.0015)	0.9948 (0.0019)	**0.9968 (0.0013)**	0.9762 (0.0071)	0.9747 (0.0082)	0.9736 (0.0081)
Specificity	0.9904 (0.0045)	**0.9927 (0.0032)**	0.9861 (0.0055)	0.8562 (0.0602)	0.8940 (0.0421)	0.8629 (0.0516)

m (s)*, m is the mean value and s is the standard deviation.

The reconstruction results of incomplete fingerprint images by using U-net and FCN models in various depths in Table 2. The reconstruction results of the U-net model with depth 5 and 6 are better than other methods.

Table 2

Reconstruction Performances of testing datasets for the proposed U-net and FCN.

Models	**U-net**			**FCN**		
Depth	**4**	**5**	**6**	**4**	**5**	**6**
MSE	0.0077 (0.0030)	**0.0060 (0.0028)**	0.0061 (0.0034)	0.0160 (0.0051)	0.0272 (0.0085)	0.0252 (0.0072)
MAE	0.0201 (0.0064)	0.0172 (0.0060)	**0.0168 (0.0059)**	0.0327 (0.0096)	0.0456 (0.0133)	0.0487 (0.0127)

m (s)*, m is the mean value and s is the standard deviation.

It is the segmentation result of the incomplete single fingerprint of the red envelope by adopting the U-net and FCN models in different depths in Figure 5. It can be seen from Figure 5 that the U-net model can completely separate the fingerprint from the red envelope under three different depths. Figure 5 (a) is the red envelope image with residual fingerprints, Figure 5 (b) is the fingerprint mask image, Figure 5 (c)-(d) are formed under different Depth U-net and FCN predict segmentation mask image. Figure 6 is the result of fingerprint reconstruction of the segmented image in which the U-net model can reconstruct the incomplete part of the fingerprint to make the fingerprint more complete. Figure 6 (a) is an image with incomplete fingerprints, Figure 6 (b) is a complete fingerprint image, Figure 6 (c)-(d) are U-net and FCN prediction reconstruction composed of different depths fingerprint image.

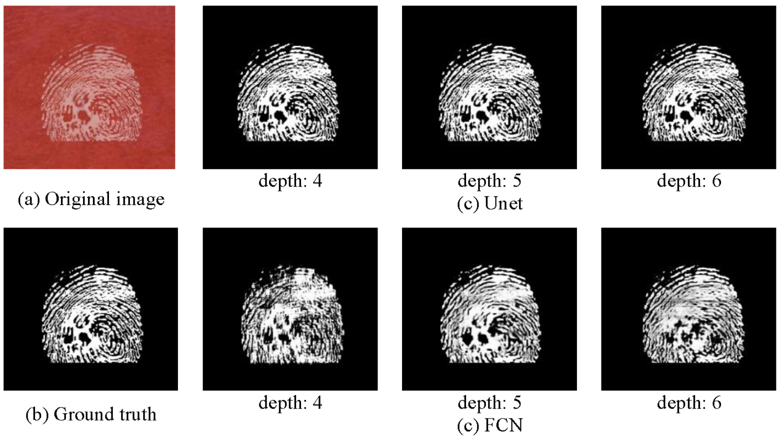


Figure 5

Segmentation results of the single fingerprint on various models.

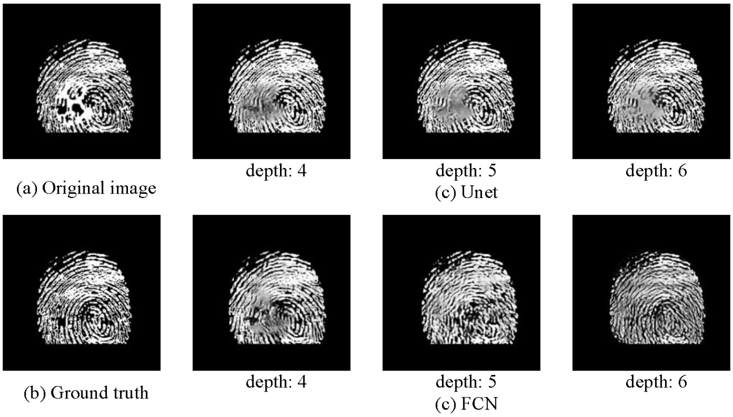


Figure 6

Reconstruction results of the single fingerprint on various models.

5. Future research

In this paper, only 1000 incomplete fingerprint images of the Easy level are used to synthesize the red envelope image which is called Fusion Image. The synthesized image is used to simulate the red envelope fingerprints collected at the crime scene. We divide the fused images into a training set and a test set with 800 and 200 images respectively and apply U-net and FCN models in various depths to reconstruct the incomplete fingerprint images. As the result, U-net model in depth 5 and 6 have mean square error 0.0060 to 0.0061 which are extremely low. At the same time, the average absolute error of U-net model depth 5 and 6 from 0.0172 to 0.0168 is also very low. The results show that the U-net deep learning method is superior to the FCN deep learning method. The fingerprint segmentation and reconstruction predicted by the U-net model on incomplete fingerprint image reconstruction results an obvious matching quality and also improves the reconstruction yield of incomplete fingerprints.

The main contribution of this paper is to separate the background of the red envelope from the incomplete fingerprint and then reconstruct the incomplete fingerprint to obtain a more complete fingerprint. As the result, it is more convenient for fingerprint identification equipment or criminal identification personnel to interpret. This research not only solves the uncertainty of incomplete fingerprints and false information collected on red envelopes but also reduces the time for front-line personnel to compare fingerprints in order to improve the efficiency of fingerprint identification. The future research can also apply this method to other materials such as plastic products, fingerprints on firearms, glass materials and securities which are common evidence at criminal scenes.

This research is to simulate the situation of incomplete fingerprints on red envelope. However, the sampling results will be affected by factors in the real situations such as shooting light, distance, angle, etc., and the fingerprints displayed by fingerprint reagents will have fingerprints' color to fade away due to the passage of time. Also, there may be decorations of different materials or plastic bags on the outer layer of the red envelope which makes it impossible to use the ethyl cyanoacrylate. In the future, the experiments will definitely be more valuable if we can sample the incomplete fingerprints on the red envelope from the real situations in order to verify the feasibility of this method.

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