

# Enhancing Fingerprint Recognition System by the Fused Edge Map

Lwin Min Paing<sup>1,3,\*</sup>, Charnchai Pluempitiwiriwaj<sup>1,3,4</sup>,  
Lunchakorn Wuttisittikulki<sup>1,2,3</sup>

<sup>1</sup>*Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand*

<sup>2</sup>*Holistic Health Care for All Research Group, Bangkok 10330, Thailand*

<sup>3</sup>*Communications and Information Engineering (CIE), Bangkok 10330, Thailand*

<sup>4</sup>*Multimedia Data Analytics and Processing Research Unit, Bangkok 10330, Thailand*

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## ABSTRACT

Biometric identification technologies such as fingerprint, facial recognition, and iris or retina scans are widely integrated into modern identity verification systems, including smartphones, computers, and smart home access control. Among these, fingerprint recognition is one of the most extensively used methods due to the uniqueness of ridge patterns in individual fingerprints. In this paper, we propose a fingerprint matching system based on edge detection techniques. Specifically, we utilize three traditional edge detection operators—Canny, Prewitt, and Sobel—to extract edge features from fingerprint images. The proposed system involves four primary steps: image pre-processing, edge detection using the three operators, fusion of the resulting edge maps, and morphological processing to enhance edge features, followed by a decision-making process based on a matching threshold. We introduce a fusion strategy, Fused Edge Map (FEM), that combines the strengths of each operator to generate a more accurate edge representation. To evaluate FEM, we apply two fusion methods: Majority-based Fusion (MF) and Union-based Fusion (UF). Experimental results show that MF achieves a fingerprint matching accuracy of 92.82%, while UF outperforms all individual edge detectors and the MF method, achieving a matching accuracy of 96.25%.

**Keywords:** Biometric identification; Edge detecting; Fingerprint recognition; Fused Edge Map (FEM)

## 1. Introduction

As technology continues to advance, reliance on digital systems has grown significantly across both personal and business domains, increasing the importance of robust authentication mechanisms. From smartphones and computers to access control systems, individuals and organizations alike seek effective methods to secure sensitive information from unauthorized access. However, many of these systems still rely on weak authentication methods such as Personal Identification Numbers (PINs) and passwords [1]. As a result, biometric identification has gained popularity due to the uniqueness of human traits, such as fingerprints, facial features, iris or retina patterns, and even DNA. Among these, fingerprint recognition is one of the oldest and most widely adopted biometric authentication methods, as the ridge patterns in fingerprints are unique to each individual and remain unchanged over time [2].

Digital image processing involves the manipulation of two-dimensional (2D) images using algorithms for tasks such as enhancement, restoration, segmentation, compression, and classification [3]. In recent years, image processing techniques have expanded across numerous fields. One advanced method in image processing is edge detection, which extracts meaningful structural information from images. Traditional edge detection techniques include Roberts, Prewitt, Sobel, and Canny operators. A survey on edge detection methods [4] highlights the progression of these techniques—from the introduction of the Roberts operator in 1963, the Canny detector in the 1970s, and Sobel in 1983, to more recent deep learning-based methods that began emerging around 2014. Edge detection has since been widely applied in various domains, including biometric identifi-

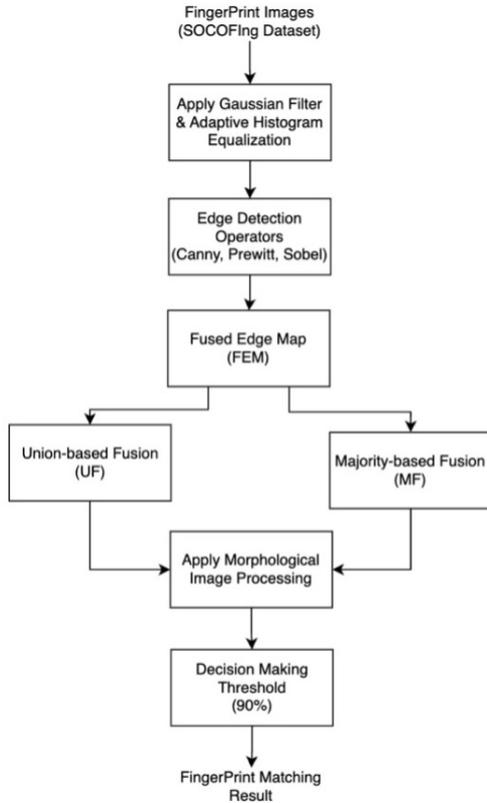
cation [5] and medical imaging [6].

In image analysis, an edge signifies a boundary indicating significant changes between adjacent regions, and can take various forms such as step edges, ramp edges, line edges, and roof edges [7, 8]. Edge detection is a discontinuity-based segmentation approach that identifies object boundaries while significantly reducing the data volume—without compromising the integrity of essential image information [9, 10]. It is a foundational technique in both computer vision and image processing fields. The performance of the fingerprint recognition system can be significantly affected by the accuracy of edge detection especially when the fingerprint images are acquired under uncontrolled conditions.

In this paper, we thus apply traditional edge detection methods—Canny, Prewitt, and Sobel—to fingerprint images as part of our proposed fingerprint matching system. These operators assist in extracting fine details such as ridge lines and minutiae points from fingerprint images. However, achieving optimal feature extraction under noisy conditions remains a challenging task as our method relies heavily on the edge detection results produced by these edge detectors. If the detected edges are not sufficiently strong, it can negatively affect our method's accuracy. Therefore, we incorporate image filtering techniques to reduce noise and enhance contrast, thereby improving the quality of edge detection. The complete process pipeline of this work is shown in Fig. 1.

The main contributions of this paper are summarized as follows:

- (1) Edge Detection on Fingerprint Images: We apply three traditional edge detection operators—Canny, Prewitt, and Sobel—to extract edge features from fingerprint images, enabling the identification



**Fig. 1.** Pipeline of the Fingerprint Matching System.

of ridge patterns and key structural information.

(2) Fusion-based Accuracy Enhancement: We enhance fingerprint matching accuracy by fusing the edge maps produced by the three operators, combining their strengths to create a more robust and accurate edge representation.

(3) Comparative Evaluation of Fusion Methods: We propose and evaluate two Fused Edge Map (FEM) strategies—Majority-based Fusion (MF) and Union-based Fusion (UF)—and compare their performance in terms of fingerprint matching accuracy.

## 2. Literature Review

### 2.1 Fingerprint recognition

Fingerprint recognition remains one of the most widely adopted biometric identification technologies in real-world applications. In [11], the authors contributed a fingerprint recognition system with edge detection and dimensional reduction techniques. They used Principle Component Analysis (PCA) and Linear Discriminant Analysis (LDA) and showed that integrating PCA and LDA in image pre-processing step can increase the fingerprint recognition rate, using PCA in conjunction with Canny edge detection operator can improve from 64.3% to 88% and while applying LDA achieved the improvement from 73.8% to 88% respectively.

In the survey on the fingerprint recognition system [12], the researchers proposed an optimal approach for better implementation such as using image enhancement, fine feature extraction and fingerprint matching techniques. For example, in [5], the authors applied Canny, Prewitt, and Sobel edge detectors in combination with the Hough Transform. Their findings showed that Sobel with Hough Transform achieved the highest fingerprint matching accuracy at 91.739%, followed by Prewitt at 89.984%, and Canny at 78.840%. This study presented a twelve-step fingerprint matching system, composed of applying edge detection twice on fingerprint images, using Canny, Prewitt, and Sobel operators, applying Hough Transform, extraction of black and white pixel points, calculation of matching accuracy percentage, a threshold as 90% is set for matching decision algorithm, and the result comparison to evaluate performance.

Recently, fingerprint recognition systems have been significantly improved with the emergence of deep learning technolo-

gies [13]–[16]. For instance, in [13], the authors employed two types of the Convolutional Neural Networks (CNNs), DenseNet-201 and ResNet-50, achieving the fingerprint recognition accuracies of 99.43% and 99.53%, respectively. Also in [14], the authors conducted five different experiments using following methods: (1) CNN, (2) CNN combined with Gabor filter, (3) Logistic Regression with principle Component Analysis (PCA) and SMOTE, (4) K-Nearest Neighbor (KNN) classifier, and (5) a hybrid approach using Multi-Layer Perceptron (MLP) and Support Vector Machine (SVM). Among these experiments, the KNN approach in experiment (4) performed the best across all set of fingerprint images from SOCOFing dataset, with a score of 0.96, followed by the experiment (1) that uses CNN approach, scored 0.94. They also discussed the advantages and limitations of both conventional and machine learning techniques for fingerprint recognition in their study.

## **2.2 Edge detection**

In [8], the authors outlined three fundamental steps of edge detection: image smoothing, edge point detection, and edge localization. Edge detection methods are generally categorized into two groups: gradient-based methods, which use first-order derivatives, and Laplacian-based methods, which rely on second-order derivatives. Edge detection is used to identify points in an image where the brightness varies significantly [17]. This technique has found wide application in areas such as smart traffic control [18] and the medical field [19]. Among various edge detectors, Canny, Prewitt, and Sobel are the most widely used traditional methods due to their balance of performance and simplicity. More recently, deep learning-based ap-

proaches have been introduced to improve edge detection in complex tasks such as object detection [20] and cancer image analysis [6].

Fingerprint recognition, a key biometric identification method, also benefits from edge detection. Several studies, including [5, 21, 22], have explored the integration of edge detection methods into fingerprint matching systems. One notable study presented in [5], the contributors integrated Hough transform into edge detection process for their fingerprint matching system.

## **2.3 Canny edge detection**

The Canny edge detector [23], developed by John F. Canny, is one of the most popular algorithms for extracting edges from images. It involves a multi-stage process that includes noise reduction, gradient calculation, non-maximum suppression, and edge tracking by hysteresis. Subsequent studies have aimed to improve the traditional Canny operator.

For instance, in [24], researchers addressed challenges such as edge detail loss and false edge detection by focusing on smoother filtering techniques and adaptive threshold selection, resulting in more reliable edge detection outcomes.

## **2.4 Prewitt edge detection**

The Prewitt edge detector [25], introduced by Judith M. S. Prewitt, is known for its ability to detect edges along both the horizontal (x-axis) and vertical (y-axis) directions. It is favored for its simplicity and fast processing.

However, a known drawback is its sensitivity to noise. In response, researchers proposed [26].

## 2.5 Sobel edge detection

The Sobel edge detector [27] operates similarly to the Prewitt operator, focusing on detecting edges along horizontal and vertical axes. Despite its effectiveness, it has limitations. For instance, [28], pointed out that the traditional Sobel operator is unable to accurately determine edge directions beyond  $0^\circ$  and  $90^\circ$ , limiting its effectiveness in capturing diagonal edges.

To overcome this, researchers introduced an extended Sobel operator using  $45^\circ$  and  $135^\circ$  directional templates along with weight adjustments to enhance its directional sensitivity and edge detection accuracy.

## 3. Method

### 3.1 Edge detection

In this work, we utilize the Sokoto Coventry Fingerprint Dataset (SOCOFing) [29] as the basis for our fingerprint matching system. The SOCOFing dataset comprises 6,000 fingerprint images from 600 African subjects, including both real and synthetically altered versions of each fingerprint. The dataset also includes metadata such as hand orientation, finger type, and gender.

To detect fingerprint edges, we apply three traditional edge detection operators—Canny, Prewitt, and Sobel—similar to the methodology in [5]. In each experiment, we select two fingerprint samples from the dataset: one real and one altered version. These images are first uploaded into MATLAB, where they are converted to grayscale to simplify processing and reduce computational complexity.

Before applying edge detection, we perform image preprocessing using two enhancement techniques:

- Gaussian filtering to suppress noise

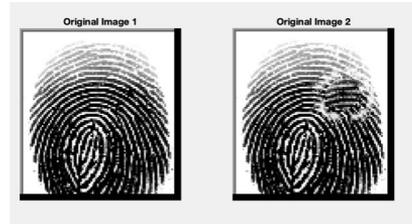


Fig. 2. Original Fingerprint Images.

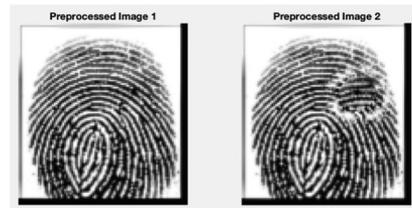


Fig. 3. Preprocessed Fingerprint Images.

- Adaptive Histogram Equalization to improve image contrast

Examples of the original and preprocessed images are shown in Figs. 2-3, respectively.

Following preprocessing, edge detection is applied to both the real and altered fingerprint images using all three operators:

- For the Canny operator, we set the low threshold to 0.1 (to detect weaker edges) and the high threshold to 0.15 (for stronger edges). A Gaussian filter with a sigma value of 1.5 is also applied as part of the Canny algorithm to smooth the image.
- For the Prewitt and Sobel operators, we apply a uniform threshold of 0.1.

After extracting edges using each operator, we proceed to fuse the results using a method called the Fused Edge Map (FEM). This method combines the detected edge maps from the three operators into a single, more accurate representation. Our fusion strategy is inspired by approaches used

in [30, 31], where edge maps from Sobel, Laplacian of Gaussian (LoG), and Canny were combined to improve detection quality.

### 3.2 Majority-based Fusion (MF)

In this step, we aim to reduce noise and enhance the accuracy of the edge maps by combining the results from the three edge detection operators. The fusion process is performed by applying logical operations on the binary edge maps obtained from the Canny, Prewitt, and Sobel operators. Let:

- C represents the edge map from the Canny Operator,
- P represents the edge map from the Prewitt Operator,
- S represents the edge map from the Sobel Operator,
- $\wedge$  represents the logical and Operation,
- $\vee$  represents the logical OR Operation.

We introduce a fusion method referred to as Majority-based Fusion (MF). In this approach, an edge pixel is retained in the fused edge map only if it is detected by at least two of the three operators. This strategy is designed to suppress false or noisy edges that may be detected by only a single operator, thereby improving the overall reliability of the edge map.

The Majority-based Fusion is mathematically defined as:

$$MF = (C \wedge P) \vee (C \wedge S) \wedge (P \wedge S). \quad (3.1)$$

This equation ensures that any edge pixel identified by at least two of the three

detectors (Canny, Prewitt, or Sobel) is preserved in the final fused result.

### 3.3 Union-based Fusion (UF)

As an alternative to the Majority-based Fusion (MF) approach, we implement Union-based Fusion (UF) to combine the edge maps produced by the three detection operators. This method utilizes the logical OR operation to merge the results from Canny (C), Prewitt (P), and Sobel (S) edge detectors. In this fusion strategy, all detected edges from the three operators are retained, ensuring that no potential edge information is lost. The goal of Union-based Fusion is to capture the maximum number of edge details, including weak or partial edges that might be missed by one or two individual operators. The Union-based Fusion is mathematically defined as:

$$UF = C \vee P \vee S. \quad (3.2)$$

While this method increases edge coverage and improves the completeness of edge detection, it may also introduce broken or incomplete edges and additional noise, as it does not filter out edges detected by only a single operator. Despite this drawback, Union-based Fusion is effective when maximizing edge detection is prioritized over strict noise suppression.

### 3.4 Fusion matching with morphological processing

For the edge maps generated using the fusion methods (MF and UF), we apply morphological image processing before computing the matching percentage. This step is crucial for reducing noise and closing gaps in the detected edges—particularly important for the UF method, which may contain more noise due to the inclusion of all detected edges.

After preprocessing, the matching percentage for our fusion strategy, Fused Edge Map (FEM), including both Majority-based Fusion (MF) and Union-based Fusion (UF), is calculated using the following formula:

$$IoU(\%) = \frac{\text{No. of common fused-edge pixels in FEM}}{\text{Total number of fused-edge pixels in FEM}} \times 100. \quad (3.3)$$

This metric is used in the final decision-making process to assess the accuracy of each fusion technique in fingerprint matching. To calculate fingerprint matching percentage, we follow the Jaccard Index also known as Intersection over Union (IoU) [32] by performing logical AND to identify the common fused-edge pixels in fingerprint images and logical OR to count all the edge pixels from two fingerprint images.

### 3.5 Decision-making algorithm

Following the application of the edge detection operators to the fingerprint images, we compute the matching percentage for each method: Canny, Prewitt, and Sobel. The edge maps are first converted from logical to double format to enable numerical computation. We adopt a matching threshold of 90%, as used in [5], to determine whether two fingerprint images are considered a match. If the matching percentage is greater than or equal to 90%, the fingerprints are classified as matched. Otherwise, if the result falls below 90%, they are classified as not matched. The matching percentage is calculated using the same formula:

$$IoU(\%) = \frac{\text{No. of common edge pixels}}{\text{Total number of edge pixels}} \times 100. \quad (3.4)$$

## 4. Results and Discussion

This work was implemented in MATLAB (R2024a) on a system equipped with

an Apple Silicon M1 chip. We applied three edge detection operators—Canny, Prewitt, and Sobel—to extract edges from fingerprint images. The detected edges using these operators and our approach FEM are illustrated in Fig. 4(a). We also demonstrated the edge detection results of Canny, Prewitt, and Sobel operators and our fusion strategy, Fused Edge Map (FEM)—Majority-based Fusion (MF) and Union-based Fusion (UF)—comparison with ground truth images in Figs. 5-6.

Following edge detection, we fused the results using two fusion strategies: Majority-based Fusion (MF) and Union-based Fusion (UF). In the MF approach, an edge is preserved only if it is detected by at least two of the three operators. The fused edges generated by MF for both fingerprint images are shown in Fig. 4(b).

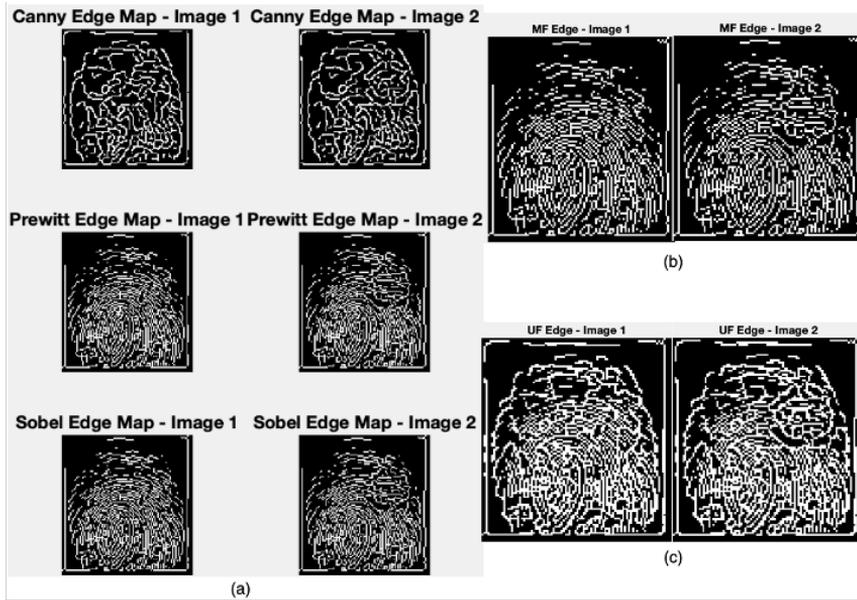
Conversely, the UF approach retains all edges detected by any of the three operators using a logical OR operation. This method captures more edge details but can introduce incomplete or noisy edges, as shown in Fig. 4(c).

To mitigate noise and address incomplete edge structures in UF, we performed morphological image processing. After processing, we calculated the matching percentages for each edge detection method, including the fused results. The results are shown in Table 1. To further highlight dif-

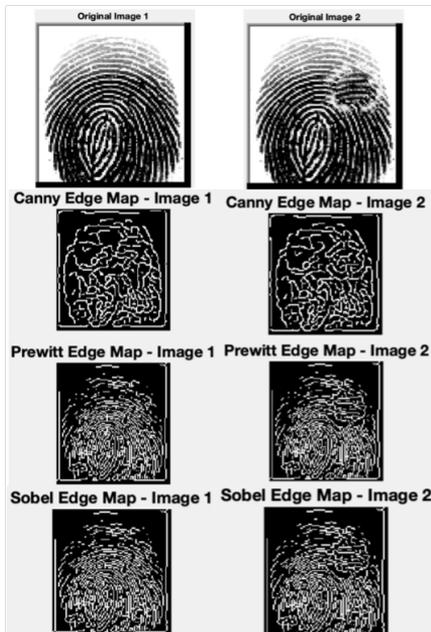
**Table 1.** Matching percentages of edge detectors and Fused Edge Map (FEM).

Edge Detection Method	Matching Percentage
Canny Operator	74.90%
Prewitt Operator	83.33%
Soble Operator	82.57%
Fused Edge Map (FEM) by MF	92.82%
Fused Edge Map (FEM) by UF	96.25%

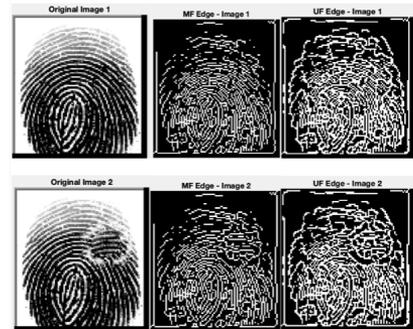
ferences between two fingerprint images, we utilized a MATLAB function to generate



**Fig. 4.** (a) Detected edges using Canny, Prewitt, and Sobel edge detection operators. (b) Majority-based Fusion (MF) method. (c) Union-based Fusion (UF) method.



**Fig. 5.** Edge detection results of Canny, Prewitt, and Sobel operators comparison with ground truth images.



**Fig. 6.** Fused Edge Map (FEM) results comparison with ground truth images.

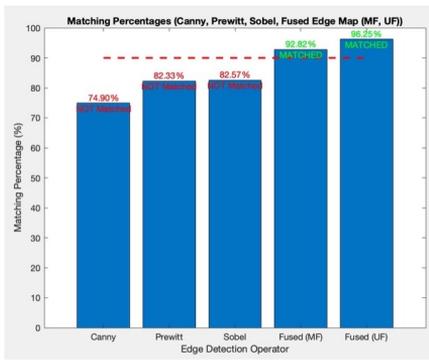
an absolute difference map, shown in Fig. 7.

We observed that Union-based Fusion (UF) resulted in the highest fingerprint matching percentage (96.25%), outperforming individual edge detectors and the MF method. Fig. 8 compares the matching percentages of all methods, including MF and UF.

To validate our approach, we em-



**Fig. 7.** Absolute difference map between two fingerprint images.



**Fig. 8.** Comparison of matching percentages, Canny, Prewitt, Sobel, FEM (MF and UF).

ployed two standard similarity metrics, Correlation Coefficient (CC) [33] and Structural Similarity Index (SSIM) [34]. We utilize CC MATLAB function to measures the linear relationship between two images.

CC can be expressed in the following Mathematical form:

$$r = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{(\sum_m \sum_n (A_{mn} - \bar{A})^2)(\sum_m \sum_n (B_{mn} - \bar{B})^2)}} \quad (4.1)$$

according to [35],  $r$  is the Pearson Corre-

lation Coefficient,  $A_{mn}$  and  $B_{mn}$  are pixel intensity values, and  $\bar{A}$  and  $\bar{B}$  are the mean pixel intensity values of images  $A$  and  $B$ , respectively.

We use SSIM in MATLAB to evaluates perceived similarity in structure, luminance, and contrast. SSIM can be expressed in the following Mathematical form:

$$SSIM(x, y) = l(x, y)^\alpha (c, y)^\beta \cdot (s, y)^\gamma, \quad (4.2)$$

where  $l$ ,  $c$ , and  $s$  represent luminance, contrast, and structure, respectively.

The CC value between the two fingerprint images was 0.9658, indicating strong correlation. The SSIM score was 0.9422, also suggesting high similarity. These results confirm that the fingerprint images are matched, supporting the reliability of our fusion-based method. We also employed CC and SSIM on the results of edge operators and our FEM (MF and UF). The results comparison in Table 2 indicate that the fingerprint images have a stronger relationship and structural similarity as CC and SSIM values are approaching +1.

**Table 2.** CC and SSIM Values for Edge Detection Methods.

Method	CC Value	SSIM Value
Original Fingerprint Images	0.9658	0.9422
Canny Edge Detection	0.8223	0.8266
Soble Edge Detection	0.8762	0.8733
Prewitt Edge Detection	0.8751	0.8692
Fused Edge Map (FEM) by MF	0.8767	0.8715
Fused Edge Map (FEM) by UF	0.8623	0.8591

## 5. Conclusion

In this paper, we present a fingerprint matching system that utilizes the Fused Edge Map (FEM) derived from three traditional edge detection operators: Canny, Prewitt, and Sobel. Prior to applying the edge detectors to the fingerprint images, we perform image preprocessing using Gaus-

sian filtering and adaptive histogram equalization to enhance the quality of the images.

We then employ the three edge detection methods within MATLAB to extract the edges from the fingerprint images and integrate them into the fingerprint matching system. The edges detected by these operators are fused using two fusion approaches: Majority-based Fusion (MF) and Union-based Fusion (UF).

In the MF an edge is retained only if it is detected by at least two of the three operators. This fusion approach results in higher matching accuracy. In the UF method, all edges detected by any of the three operators are preserved, combining them to achieve the highest possible detection rate. However, this method is more prone to noise, which is mitigated by applying morphological image processing before calculating the final matching percentage.

We demonstrate that our Fused Edge Map (FEM) significantly improves fingerprint recognition accuracy compared to the individual Canny, Prewitt, and Sobel edge detection operators. Our results show that the Union-based Fusion (UF) approach yields the highest matching accuracy, offering a robust and reliable solution for fingerprint matching.

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