

# LATENT FINGERPRINT DETECTION FOR DIGITAL FORENSICS INVESTIGATION

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**Abstract-**Latent fingerprint detection is a critical component of digital forensic investigation, enabling reliable personal identification in criminal analysis. However, conventional fingerprint examination techniques often encounter limitations due to poor image quality, low contrast, noise, and incomplete ridge patterns. This paper presents a MATLAB-based framework for latent fingerprint detection and enhancement using advanced digital image processing techniques. The proposed methodology incorporates image acquisition, grayscale conversion, noise reduction, contrast enhancement, segmentation, ridge enhancement, binarization, and thinning operations to improve fingerprint visibility and clarity. Furthermore, Gabor filtering and morphological processing are employed to enhance ridge structures while suppressing background artifacts and noise. The enhanced fingerprint images enable accurate extraction of minutiae features such as ridge endings and bifurcations, which are essential for forensic identification and verification. MATLAB serves as an efficient platform for implementing and evaluating the proposed algorithms due to its strong computational and visualization capabilities. Experimental results demonstrate significant improvement in the quality and interpretability of latent fingerprints obtained from diverse surfaces and environmental conditions. The proposed system supports accurate forensic analysis, enhances evidence interpretation, and assists investigators in reliable identity verification. The study emphasizes the importance of digital image processing in modern forensic systems and presents a cost-effective, efficient, and reproducible solution for forensic laboratories and law enforcement agencies.

**Keywords-**Latent fingerprint detection, digital image processing, forensic investigation, MATLAB, Gabor filtering, fingerprint enhancement, minutiae extraction, ridge enhancement, image segmentation, forensic identification

## 1. INTRODUCTION

Latent fingerprints are among the most significant forms of biometric evidence used in forensic science for personal identification and criminal investigation. Due to the uniqueness and permanence of fingerprint ridge patterns, fingerprint analysis has become a reliable method for verifying an individual's identity in law enforcement and security applications. Unlike visible fingerprints, latent fingerprints are typically invisible to the naked eye and are unintentionally left on surfaces through sweat, oil, or other biological residues. Detecting and enhancing such

fingerprints is a challenging task because latent impressions are often affected by noise, poor contrast, smudging, background interference, and incomplete ridge structures.

Traditional fingerprint examination methods rely heavily on manual inspection and chemical enhancement techniques, which may not always provide satisfactory results under varying environmental and surface conditions. With the rapid advancement of digital image processing technologies, automated fingerprint enhancement techniques have gained considerable attention in modern forensic systems. Image processing methods improve the visibility of ridge patterns and assist forensic experts in extracting important minutiae features such as ridge endings and bifurcations, which are essential for accurate fingerprint matching and identification. Several approaches have been proposed for fingerprint enhancement using filtering, segmentation, morphological operations, and feature extraction methods. Among these, Gabor filtering has proven highly effective for enhancing ridge frequency and orientation while reducing noise and unwanted artifacts. Similarly, morphological processing and thinning operations contribute to improving ridge continuity and preparing fingerprint images for minutiae extraction. The integration of these techniques enables the development of robust and efficient automated fingerprint analysis systems.

The primary objective of this research is to enhance the quality of latent fingerprint images obtained from different surfaces and environmental conditions while minimizing background noise and distortions. Experimental evaluation demonstrates that the proposed approach significantly improves fingerprint visibility and facilitates effective minutiae extraction for accurate identity verification. The developed framework offers a cost-effective, efficient, and reproducible solution for forensic laboratories and law enforcement agencies involved in criminal investigations and digital forensic analysis.

## 2. SYSTEM ARCHITECTURE

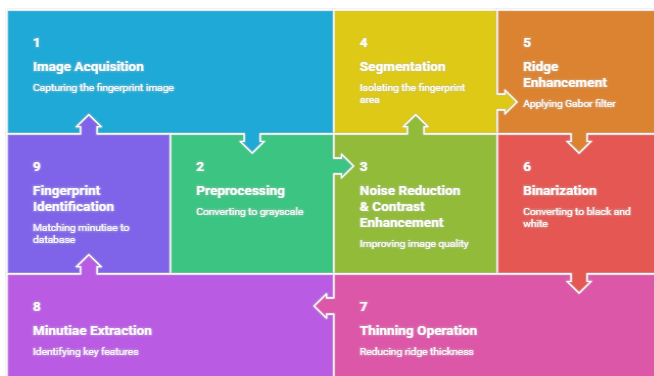
**Proposed Architecture:** The proposed latent fingerprint detection system is designed using a sequence of digital image processing stages implemented in MATLAB. The architecture focuses on improving the visibility and quality of latent fingerprint images for accurate forensic identification. The system processes fingerprint images through multiple enhancement and feature extraction stages to obtain clear ridge patterns and reliable minutiae information.

The overall architecture of the proposed system consists of the following modules:

### Image Acquisition

1. **Preprocessing**
2. **Noise Reduction and Contrast Enhancement**
3. **Segmentation**
4. **Ridge Enhancement**
5. **Binarization**
6. **Thinning Operation**
7. **Minutiae Extraction**
8. **Fingerprint Analysis and Identification**

The workflow of the proposed system is illustrated in Fig. 1.



### Workflow

- A. **Image Acquisition**- The first stage involves acquiring latent fingerprint images from various surfaces using image sensors or forensic imaging devices. The captured images may contain noise, low contrast, and unwanted background patterns, requiring further enhancement for effective analysis.
- B. **Preprocessing**- In the preprocessing stage, the acquired fingerprint image is converted into grayscale format to simplify processing and reduce computational complexity. Basic normalization techniques are applied to standardize image intensity levels. Ridge Enhancement.
- C. **Ridge enhancement** is performed using Gabor filtering and morphological operations. Gabor filters enhance ridge orientation and frequency characteristics while suppressing noise and background artifacts. Morphological operations improve ridge continuity and structure.
- D. **Binarization**-The enhanced grayscale image is converted into a binary image where ridges are represented by black pixels and valleys by white pixels. This simplifies the extraction of fingerprint features.

- E. **Thinning Operation**- Thinning reduces ridge thickness to a single-pixel width while preserving ridge connectivity. This operation is essential for accurate minutiae detection.
- F. **Minutiae Extraction**-The system extracts important minutiae features such as ridge endings and bifurcations from the thinned fingerprint image. These features are widely used for fingerprint matching and forensic identification.
- G. **Fingerprint Identification**-The extracted minutiae are analyzed and compared for identity verification and forensic investigation. The enhanced fingerprint patterns improve matching accuracy and support reliable criminal identification.

### 3. OBJECTIVES

The primary objective of this research is to develop an efficient MATLAB-based latent fingerprint detection and enhancement system for forensic investigation. The proposed work aims to improve the quality and visibility of latent fingerprint images obtained from different surfaces and environmental conditions. The specific objectives of the study are as follows:

1. To acquire and process latent fingerprint images for forensic analysis.
2. To enhance low-quality fingerprint images by applying digital image processing techniques such as filtering, contrast enhancement, segmentation, and ridge enhancement.
3. To reduce background noise and unwanted artifacts present in latent fingerprint images.
4. To improve ridge clarity and continuity using Gabor filtering and morphological operations.
5. To perform binarization and thinning operations for accurate fingerprint structure representation.
6. To extract minutiae features such as ridge endings and bifurcations for reliable fingerprint identification.
7. To implement and evaluate the proposed fingerprint enhancement framework using MATLAB.
8. To provide a cost-effective, efficient, and reproducible solution for forensic laboratories and law enforcement agencies.

### 4. METHODOLOGY

The proposed methodology for latent fingerprint detection and enhancement consists of a sequence of digital image processing stages implemented in MATLAB. Each stage contributes to improving fingerprint quality and enabling accurate minutiae extraction for forensic identification. The overall workflow of the methodology is illustrated through the following steps.

- A. Image Acquisition- Latent fingerprint images are collected from different surfaces using forensic imaging devices or digital sensors. The acquired images may contain noise, poor contrast, smudges, and background interference due to environmental conditions and surface irregularities.
- B. Grayscale Conversion-The acquired color fingerprint images are converted into grayscale images to simplify further processing and reduce computational complexity. Grayscale conversion preserves important ridge information while eliminating unnecessary color components.
- C. Noise Reduction-Noise reduction techniques such as median filtering and Gaussian filtering are applied to remove unwanted disturbances and improve image smoothness. These filters help suppress impulse noise while preserving fingerprint ridge structures.
- D. Contrast Enhancement- Contrast enhancement techniques are used to improve the distinction between fingerprint ridges and valleys. Histogram equalization and intensity normalization methods enhance the visibility of latent fingerprint patterns.
- E. Segmentation- Segmentation isolates the fingerprint region from the background area. This process removes irrelevant image portions and focuses only on the effective fingerprint area required for feature extraction and analysis.
- F. Ridge Enhancement- Ridge enhancement is performed using Gabor filtering and morphological operations. Gabor filters enhance local ridge orientation and frequency characteristics, while morphological processing improves ridge continuity and suppresses background artifacts.
- G. Binarization- The enhanced grayscale image is converted into a binary image in which fingerprint ridges are represented by black pixels and valleys by white pixels. Binarization simplifies fingerprint representation and prepares the image for thinning operations.
- H. Thinning Operation-Thinning algorithms are applied to reduce ridge thickness to a single-pixel width while preserving ridge connectivity and structural information. This step is important for accurate minutiae extraction.
- I. Minutiae Extraction- Minutiae features such as ridge endings and bifurcations are extracted from the thinned fingerprint image. These unique features form the basis for fingerprint matching and identity verification in forensic applications.

- J. Performance Evaluation-The proposed system is evaluated using different latent fingerprint samples obtained under varying environmental conditions and surface types. The quality of enhancement and effectiveness of minutiae extraction are analyzed to assess the performance of the framework.

## 5. DATASET AND PREPROCESSING

The dataset used in this research consists of latent fingerprint images collected from different surfaces and environmental conditions to evaluate the effectiveness of the proposed enhancement framework. The fingerprint samples include impressions obtained from glass, metal, plastic, paper, and other commonly encountered forensic surfaces. The collected images vary in quality due to factors such as smudging, partial impressions, uneven pressure, lighting variations, and background noise.

For experimental analysis, grayscale and color fingerprint images are considered to test the robustness of the proposed system. The dataset contains fingerprint samples with different ridge orientations, contrast levels, and noise distributions to simulate real-world forensic scenarios. The fingerprint images are stored in standard image formats such as JPG, PNG, and BMP and processed using MATLAB.

The dataset is categorized into the following groups:

1. **High-quality latent fingerprints** – Images with clear ridge structures and minimal noise.
2. **Low-contrast fingerprints** – Images with weak ridge visibility and poor illumination.
3. **Noisy fingerprint images** – Images affected by background interference, smudges, or sensor noise.
4. **Partial fingerprint impressions** – Incomplete fingerprint patterns containing limited ridge information.

The use of diverse fingerprint samples ensures proper evaluation of the proposed enhancement and minutiae extraction techniques under varying forensic conditions.

### Preprocessing

Preprocessing is an important stage in latent fingerprint analysis as it improves image quality and prepares the fingerprint image for further enhancement and feature extraction. The preprocessing stage aims to remove noise, improve ridge visibility, and standardize the fingerprint image for reliable analysis.

The preprocessing steps used in the proposed system are described below.

- 1) Image Resizing- The acquired fingerprint images are resized to a standard resolution to maintain uniformity during processing and reduce computational complexity. Image resizing ensures consistent analysis across all fingerprint samples.

2) Grayscale Conversion- Color fingerprint images are converted into grayscale images to simplify image processing operations. Grayscale conversion reduces data complexity while preserving essential ridge and valley information required for enhancement.

3) Noise Reduction- Fingerprint images often contain noise caused by environmental conditions, sensor limitations, and surface irregularities. Noise reduction techniques such as median filtering and Gaussian filtering are applied to remove unwanted distortions while preserving ridge continuity.

- Median filtering **removes impulse noise and salt-and-pepper disturbances.**
- Gaussian filtering **smooths the image and reduces high-frequency noise components.**

4) Contrast Enhancement- Contrast enhancement improves the visibility of fingerprint ridges and valleys. Histogram equalization and intensity normalization techniques are applied to increase the distinction between foreground fingerprint patterns and the background region.

5) Image Normalization- Normalization standardizes pixel intensity values across the fingerprint image to reduce illumination variations and improve consistency during processing. This step helps achieve better ridge enhancement results.

6) Segmentation-Segmentation separates the fingerprint region from the background area. The process identifies the region of interest (ROI) containing useful ridge information while removing unnecessary image portions and artifacts.

7) Morphological Processing-Morphological operations such as dilation and erosion are used to refine fingerprint structures and remove small unwanted objects. These operations improve ridge connectivity and reduce gaps in fingerprint patterns.

## 6. RESULTS AND DISCUSSION

The proposed MATLAB-based latent fingerprint detection and enhancement system was evaluated using multiple latent fingerprint images collected from different surfaces and environmental conditions. The experimental results demonstrate that the implemented image processing techniques significantly improve the visibility, clarity, and quality of latent fingerprint patterns, enabling effective forensic analysis and minutiae extraction.

The system was tested on fingerprint images affected by low contrast, background noise, smudging, and partial impressions. Each processing stage contributed to improving the fingerprint structure and reducing unwanted distortions. The performance of the proposed framework was analyzed based on image clarity, ridge continuity, noise suppression, and minutiae detection accuracy.

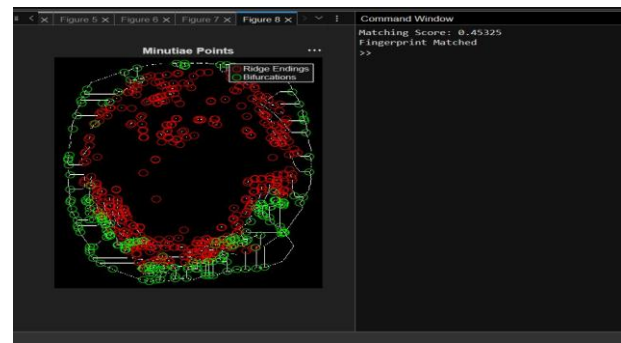


Fig. 2 Comparison between single reference

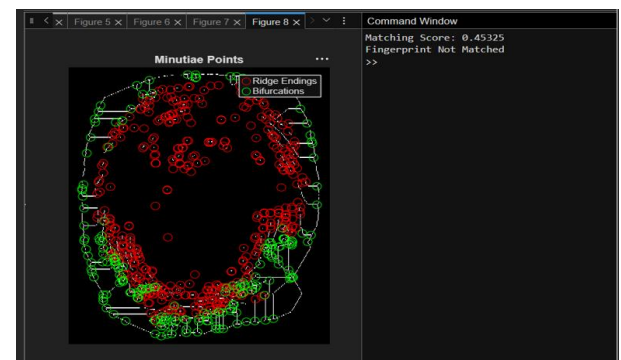


Fig. 3 Comparison between single reference

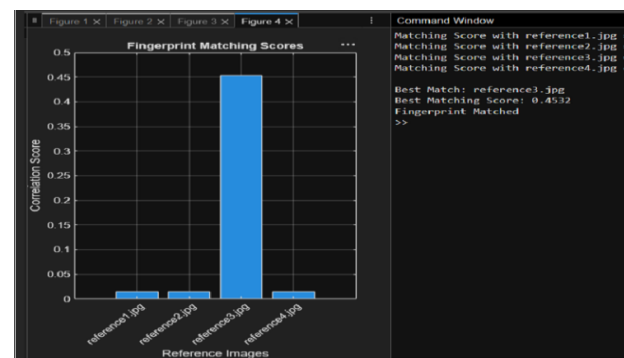


Fig. 4 Comparison between Multiple reference

## 7. CONCLUSION

This paper presented a MATLAB-based latent fingerprint detection and enhancement framework for forensic investigation using advanced digital image processing techniques. The proposed system was designed to improve the visibility and quality of latent fingerprint images affected by noise, poor contrast, smudging, and background interference. The methodology incorporated preprocessing, noise reduction, contrast enhancement, segmentation, Gabor filtering, morphological processing, binarization, thinning, and minutiae extraction to obtain clear and reliable fingerprint patterns.

Experimental results demonstrated that the proposed framework significantly enhanced ridge visibility and continuity while effectively suppressing unwanted noise and artifacts. The enhanced fingerprint images enabled accurate extraction of minutiae features such as ridge endings and

bifurcations, which are essential for fingerprint matching and identity verification. The integration of Gabor filtering and morphological operations proved highly effective in improving latent fingerprint clarity under different environmental and surface conditions.

The use of MATLAB provided an efficient and flexible platform for implementing and evaluating the image processing algorithms. The developed system offers a cost-effective, reproducible, and automated solution for forensic laboratories and law enforcement agencies involved in criminal investigations and biometric identification.

The study highlights the importance of digital image processing techniques in modern forensic science and demonstrates their capability to improve latent fingerprint analysis. Future work may focus on integrating machine learning and deep learning approaches for automated fingerprint classification, real-time identification, and improved performance on highly degraded fingerprint images.

## REFERENCES

- [1] Y. Zhu, X. Yin, and J. Hu, "FingerGAN: A constrained fingerprint generation scheme for latent fingerprint enhancement," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 45, no. 7, pp. 8358–8371, Jul. 2023.
- [2] R. Jhansi Rani and K. Vasanth, "An effective latent fingerprint enhancement and recognition system using dictionary learning and LCPnet mechanisms," *J. Intell. Fuzzy Syst.*, vol. 43, no. 5, pp. 6093–6108, 2022.
- [3] A. Alotaibi, M. Hussain, H. AboAlSamh, W. Abdul, and G. Bebis, "Cross-sensor fingerprint enhancement using adversarial learning and edge loss," *Sensors*, vol. 22, no. 18, p. 6973, Sep. 2022.
- [4] A. W. Wahab, T. M. Khan, S. Iqbal, B. AlShammari, B. Alhaqbani, and I. Razzak, "Latent fingerprint enhancement for accurate minutiae detection," *Procedia Comput. Sci.*, vol. 246, pp. 1558–1567, 2024.
- [5] A. B. V. Wyzykowski and A. K. Jain, "A universal latent fingerprint enhancer using transformers," *arXiv preprint arXiv:2306.00231*, 2023.
- [6] S. Greenberg, M. Aladjem, D. Kogan, and I. Dimitrov, "End-to-end latent fingerprint enhancement using multi-scale generative adversarial network," *Pattern Recognit. Lett.*, vol. 184, pp. 169–175, Aug. 2024.
- [7] Z. Pan, X. Guan, Y. Duan, J. Feng, and J. Zhou, "Fixed-length dense fingerprint representation with alignment and robust enhancement," *IEEE Trans. Inf. Forensics Security*, vol. 21, pp. 1751–1765, 2026.
- [8] R. Dhaneshwar, M. Kaur, M. Kaur, and V. Gupta, "Patch-based latent fingerprint recognition: A novel approach for reliable identification of partial prints," *J. Forensic Sci.*, vol. 71, no. 1, pp. 241–257, Jan. 2026.
- [9] R. Dhaneshwar, M. Kaur, and M. Kaur, "An investigation of latent fingerprinting techniques," *Egyptian J. Forensic Sci.*, vol. 11, no. 33, pp. 1–18, 2021.
- [10] M. Liu and P. Qian, "Automatic segmentation and enhancement of latent fingerprints using deep nested UNets," *IEEE Trans. Inf. Forensics Security*, vol. 16, pp. 1709–1719, 2022.
- [11] K. Horapong, K. Srisutheenon, and V. Areekul, "Progressive and corrective feedback for latent fingerprint enhancement using boosted spectral filtering and spectral autoencoder," *IEEE Access*, vol. 9, pp. 96288–96308, 2022.
- [12] S. Gu, J. Feng, and J. Lu, "Latent fingerprint registration via matching densely sampled points," *IEEE Trans. Inf. Forensics Security*, vol. 16, pp. 1231–1244, 2022.
- [13] D. Yoo, J. Cho, and J. Lee, "FinSNet: End-to-end separation of overlapped fingerprints using deep learning," *IEEE Access*, vol. 8, pp. 209020–209029, 2022.
- [14] W. Wong and S. Lai, "Multi-task CNN for restoring corrupted fingerprint images," *Pattern Recognit.*, vol. 101, pp. 1–18, 2022.
- [15] J. Li, J. Feng, and C.-C. J. Kuo, "Deep convolutional neural network for latent fingerprint enhancement," *Signal Process. Image Commun.*, vol. 60, pp. 52–63, 2022.
- [16] S. Choi, M. Boaventura, I. A. G. Boaventura, and A. K. Jain, "Automatic segmentation of latent fingerprints," in *Proc. IEEE Int. Conf. Biometrics Theory, Appl. Syst.*, 2022, pp. 1–6.
- [17] S. Bergmann, D. Moussa, and C. Riess, "Polished pixels: Impact of AI compression on image-based evidence," *Multimedia Tools Appl.*, vol. 85, no. 95, pp. 1–20, 2026.
- [18] A. K. Jain and A. Ross, "Advances in biometric fingerprint recognition systems," *IEEE Access*, vol. 11, pp. 45520–45538, 2023.
- [19] U. U. Deshpande, V. S. Malemath, S. M. Patil, and S. V. Chaugule, "End-to-end automated latent fingerprint identification with improved DCNN-FFT enhancement," *Frontiers Robot. AI*, vol. 7, p. 594412, Nov. 2020.
- [20] A. B. V. Wyzykowski and A. K. Jain, "Transformer-based latent fingerprint enhancement for forensic applications," *Pattern Recognit.*, vol. 152, pp. 110–124, 2025.