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Towards More Reliable Biometric Systems: Advanced Fingerprint Image Quality Enhancement Techniques

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Abstract **-** Fingerprints is one of the important biometrics for personal identity verification. However, the fingerprint data collection process frequently faces challenges associated to image quality, for instance job-related characteristics that involve frequent use of hands, injuries, or critical environmental conditions like cold weather that causes dry skin or humidity that leads to sweating. These factors can outcome in low-quality fingerprint images, dropping the effectiveness of the identity authentication system. This research illustrated an approach to improving the quality of fingerprint images using the proposed algorithm based on Gabor Filter processes with the Adaptive Histogram Equalization and Contrast to enhance sharpness and reduce noise of the original image. The experimental results was evaluated by using the NIST Fingerprint Image Quality 2 system (NFIQ2). The results show that the proposed algorithm significantly improve the fingerprint image quality. The Proposed approach demonstrates substantial performance gains in critical instances such as Image_06 and Image_09, exhibiting remarkable improvements of 133.3% and 153.3%, respectively. These findings collectively underscore the consistent and significantly enhanced performance offered by the Proposed method in comparison to the standard Gabor filter and Wavelet Transform techniques. The results support the efficacy of the proposed method for improving fingerprint image quality in biometric systems.

Keywords**:** Fingerprints, Image Quality, Adaptive histogram, Gabor Filter, Improvement

1. Introduction

Fingerprint patterns are unique biological characteristics widely utilized for personal identification and authentication. These patterns consist of raised ridges located on the palmar surface of the fingers, and are uniquely individual even among identical twins. Moreover, fingerprints remain unchanged throughout a person's lifetime, although the ridge patterns become more distinct with age [1]. Due to their uniqueness and permanence, fingerprints serve as a highly effective tool for identity verification in various domains such as law enforcement, security systems, access control, and forensic investigations[2]. Their high accuracy and reliability continue to make fingerprint recognition a preferred method in applications requiring strict identification standards [3].

Fingerprint-based identification is one of the most prominent biometric technologies and has garnered increasing attention in both academic research and industrial applications. A wide range of algorithms and techniques have been developed to enhance fingerprint recognition, with their performance largely dependent on the quality of the fingerprint images used. However, acquiring high-quality fingerprint images remains a significant challenge due to several influencing factors such as dry or wet skin, injuries, bruises, sensor noise, improper finger pressure, and worn ridge patterns from aging or labour-intensive work. These factors can result in low-quality fingerprint images that hinder the recognition process [4].

To address these challenges, fingerprint image enhancement techniques have become a focal point of research. Commonly employed methods include Fourier Transform, Wavelet Transform, Histogram Equalization and Gabor Filtering. These techniques play a critical role in enhancing elevation clarity, reducing noise, and improving the extraction of noticeable features. Nonetheless, each technique comes with its own strengths and limitations. For instance, Gabor Filtering is effective in enhancing directional ridge structures, Fourier Transform excels in frequency domain filtering, Histogram Equalization improves image contrast, and Wavelet Transform is capable of multi-level noise reduction [5].

This study aims to investigate methods for enhancing the quality of fingerprint images base on the Gabor filtering and proposed adaptive image processing techniques. The primary objective is to explore new approaches for improving fingerprint image quality. Therefore, to evaluate the success of the enhancement techniques, the NFIQ2 algorithm is employed to assess the quality of the fingerprint images after enhancement, with a focus on measuring image clarity and feature visibility. The effectiveness of the proposed algorithm will be evaluated by comparing fingerprint images before and after enhancement, with the goal of demonstrating its ability to significantly improve image quality. This advancement holds particular significance for security and law enforcement applications.

Therefore, the paper will describe the related works in the section 2. The third section is NFIQ2 methodology. The next session describes the research methodology. After that is the proposed algorithm and follow by the experimental results and Analysis. The final section is conclusion and discussion.

2. Related works

2.1. Wavelet Transform

Wavelet Transform enhances fingerprint image quality by decomposing the image into multiple resolution levels, allowing significant features, such as ridge patterns, to be separated from noise[6].By selectively suppressing noise components and enhancing important details at appropriate scales, the clarity and overall quality of the fingerprint image are improved, thereby facilitating more accurate analysis and identification.

2.2. Gabor Filtering

Gabor filtering enhances fingerprint image quality by applying directional and frequency-selective filters that are tuned to the local ridge orientation and frequency. This process amplifies ridge structures while suppressing noise, preserving the intrinsic patterns of the fingerprint and significantly improving the image clarity for subsequent feature extraction and matching. The enhancement process follows several key steps [7]:

Normalization

This step standardizes the grayscale intensity of the fingerprint ridges and valleys to ensure consistent processing in subsequent stages, without altering the fingerprint's ridge structure.

Orientation Estimation

Orientation estimation involves calculating the gradient of pixel intensities in local neighborhoods to determine ridge direction. Accurate orientation estimation enhances both image processing and fingerprint classification.

Region Mask Generation

In this step, the image is segmented into two categories: regions of interest (processable areas) and unrecoverable regions (e.g., areas with excessive noise or missing ridge structures). Only regions of interest are used for further analysis.

Filtering

Gabor filters are applied to the fingerprint image to suppress noise while enhancing the ridge-valley structures. These filters can be tuned for specific frequencies and orientations, making them particularly effective in fingerprint enhancement [8].

2.3. Histogram Equalization

Adaptive Histogram Equalization is an enhancement of the standard histogram equalization technique, developed to overcome its limitations [9]. Rather than computing the histogram of the entire image, It divides the image into smaller local regions (filter windows) and computes histograms within each region. This localized approach allows for more appropriate contrast enhancement tailored to image details in each area. However, a known drawback of Adaptive Histogram Equalization is the potential for over-amplification of noise, particularly in low-contrast regions, which may lead to image distortion instead of improved clarity.

2.5. Adaptive Contrast

Adaptive contrast enhancement improves fingerprint image quality by locally adjusting the intensity levels to enhance the visibility of ridge structures. By dynamically increasing contrast based on the characteristics of different regions, this method highlights fine details without over-amplifying noise or distorting other image areas, thereby facilitating more reliable feature extraction[10].

3. National Institute of Standards and Technology Fingerprint Image Quality 2

National Institute of Standards and Technology Fingerprint Image Quality 2 (NFIQ2) Algorithm developed by the U.S. National Institute of Standards and Technology (NIST). The NFIQ2 algorithm is designed to evaluate fingerprint image quality in biometric systems. It improves upon the original NFIQ1 by offering more accurate assessments of fingerprint utility and is optimized for plain fingerprint impressions acquired from 500 dpi sensors [11]. Implemented in C/C++, NFIQ2 utilizes the FingerJet FX OSE minutiae extractor and operates as follows:

3.1. Feature Extraction

The algorithm extracts quality-related features from the image and uses a Random Forest Classifier to predict the utility of the fingerprint image.

3.2. Quality Scoring

The utility score is assigned on a scale from 0 to 100, in accordance with ISO/IEC 29794-1:2016. A score of “0” indicates no utility (i.e., unusable for biometric recognition), while “100” represents the highest utility. Importantly, the concept of "utility" encompasses more than image clarity; it reflects the image's suitability for use in biometric systems, such as the ability to extract meaningful features. Even if parts of the image appear visually clear, a score of “0” suggests the image cannot meet the operational requirements of biometric systems.

4. Research Methodology

This study aims to develop an algorithm for fingerprint image enhancement and to evaluate its performance using the NFIQ2 algorithm as a benchmark for assessing image quality before and after enhancement. The overall research process is illustrated in Figure 1, which outlines the methodology in sequential stages.

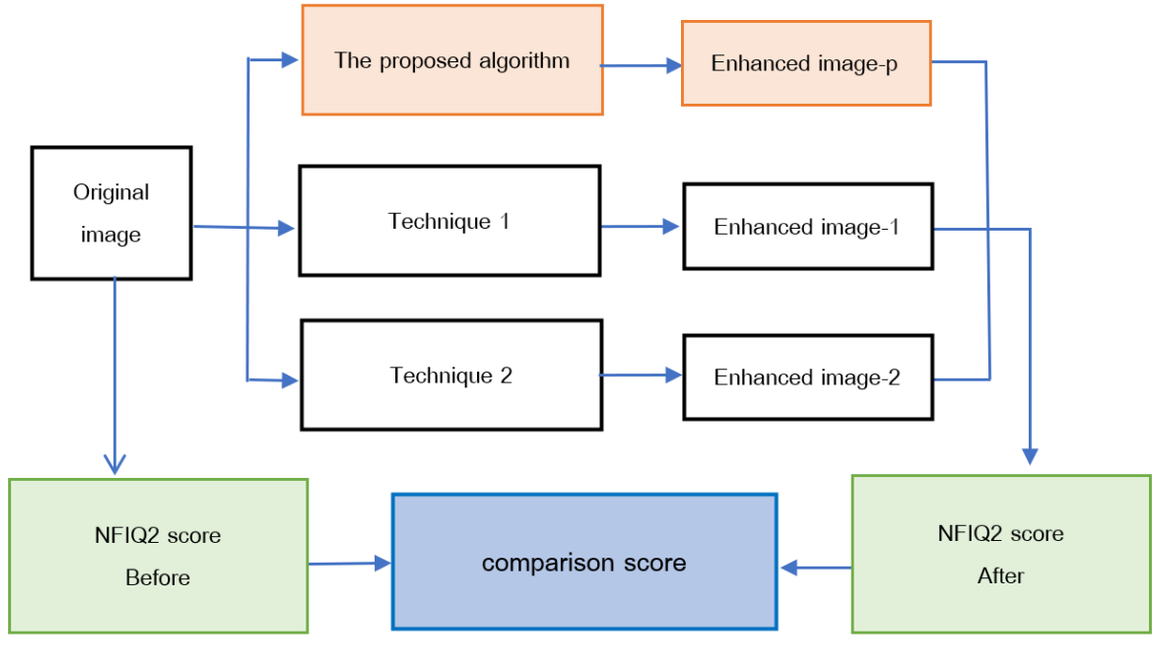

Fig. 1: Fingerprint Image Enhancement Workflow in this research

The workflow for fingerprint image enhancement starts with the acquisition of the original fingerprint image, followed by the calculation of its initial NFIQ2 quality score. The original image is then processed through multiple enhancement techniques, including the proposed algorithm and several existing methods (Technique 1 and 2). Each technique produces an enhanced fingerprint image, which is subsequently evaluated using the NFIQ2 metric to obtain post-enhancement quality scores. Finally, a comparison of the NFIQ2 scores before and after enhancement is conducted to assess the effectiveness of each method, with the goal of demonstrating the improvements achieved by the proposed approach over conventional techniques.

5. The proposed algorithm

In this research, the new algorithm will be presented and its base on the improvement of the Gabor filter as demonstrates the process of the proposed algorithm in fig. 2. Initially, an input image undergoes adaptive histogram equalization. This technique is a form of contrast enhancement that modifies the local contrast of an image. This study utilizes Adaptive Histogram Equalization to improve image sharpness and enhance the visibility of fingerprint features prior to the application of advanced enhancement techniques. The Gabor filter is applied to accentuate the ridge-valley patterns of the fingerprint images. The output image, which was enhanced by the proposed algorithm will be process in NFIQ2 to given the score.

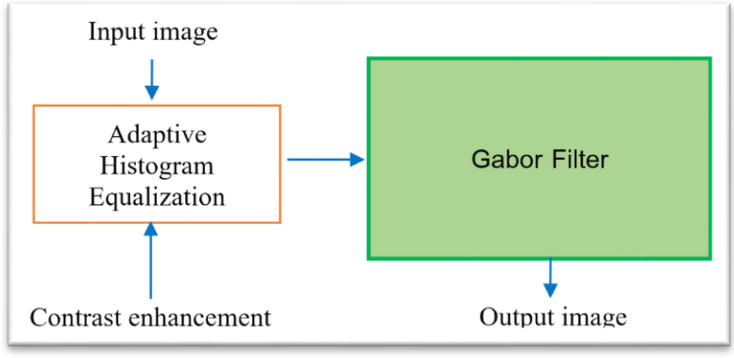

Fig.2. The proposed algorithm to improve the Figure print Enhancement

6. Experimental Results and Analysis

This study utilizes fingerprint images from the NIST Special Database 302, comprising a total of 10 images scanned at a resolution of 500 PPI (Pixels Per Inch). These images were collected from various individuals and exhibit a range of quality characteristics, including differences in fingerprint clarity and noise levels [12]. Some images suffer from common scanning issues, such as blurring and distortion, resulting in low-quality fingerprints that are unsuitable for direct use without enhancement.

In Figure 3 (a),(b),(c) and (d) show the original fingerprint images are presented, illustrating unclear ridge patterns and missing segments, which contribute to the overall low image quality and correspondingly low NFIQ2 scores.

Fig.3. The fingerprint images (a), (b), (c) and (d) prior to the enhancement process.

Following the enhancement process using the proposed algorithm to enhanced images and the outputs shown in Fig 4 (e), (f), (g) and (h) exhibit significantly improved clarity. The previously missing ridge structures have been reconstructed, resulting in enhanced detail and overall fingerprint image quality. This visual improvement aligns with the increased NFIQ2 scores, affirming the effectiveness of the proposed enhancement approach.

The resulting quality scores both before and after enhancement are compared to assess the performance of the proposed algorithm. The outcome of this evaluation provides a quantitative measure of the algorithm's effectiveness in enhancing fingerprint image quality, specifically in terms of clarity and usability for biometric system applications.

(e) (f) (g) (h)

Fig.4. The fingerprint images (e),(f),(g) and (h) after enhancement using the proposed algorithm

The experimental was perform for 10 example fingerprint images. Each image performs all the enhancement techniques and measure the NFIQ2 score as demonstrated in Table 1. The experimental results indicate that when fingerprint images are processed using the proposed enhancement algorithm which are based on the Gabor Filtering and combining Adaptive Histogram Equalization, the resulting images yield higher NFIQ2 quality scores compared to those enhanced by other techniques.

Moreover, the percentage of the improvement of each technique have been process as shown in Table 1. The percentage of the improvement be calculated via equation 1. Percentage Improvement (% Improvement) is a metric used to quantify how much a new value has improved relative to a baseline or original value. A higher percentage Improvement indicates that the applied technique has significantly enhanced performance. Conversely, a low or negative percentage Improvement suggests that the new technique offers minimal benefit or may even degrade performance compared to the original method.

$$\% \text{ Improvement} = \left(\frac{\text{New Value} - \text{Original Value}}{\text{Original Value}} \right) \times 100 \tag{1}$$

Table 1: The NFIQ2 Score and the percentage of improvement of each technique

Image	Original	Enhancement techniques			Percentage of Improvement		
		Wavelet	Gabor	Proposed	Wavelet	Gabor	Proposed
Image_01	24	27	58	60	12.5	141.7	150.0
Image_02	27	28	58	60	3.7	114.8	122.2
Image_03	25	31	45	50	24.0	80.0	100.0
Image_04	24	25	55	56	4.2	129.2	133.3
Image_05	17	17	31	32	0.0	82.4	88.2
Image_06	18	20	37	42	11.1	105.6	133.3
Image_07	35	41	48	53	17.1	37.1	51.4
Image_08	13	25	30	31	92.3	130.8	138.5
Image_09	30	32	71	76	6.7	136.7	153.3
Image_10	51	57	52	60	11.8	2.0	17.6

The column labeled "Original" reflects the raw NFIQ2 scores before any enhancement. The subsequent columns represent the scores after applying each enhancement technique. From the results, it is evident that the Proposed Algorithm consistently yields the highest NFIQ2 scores across all ten images. Fig.5. illustrates the comparative of NFIQ2 Scores of four methods: Original, Wavelet Transform, Gabor Filter, and the Proposed method, evaluated across a dataset of 10 images.

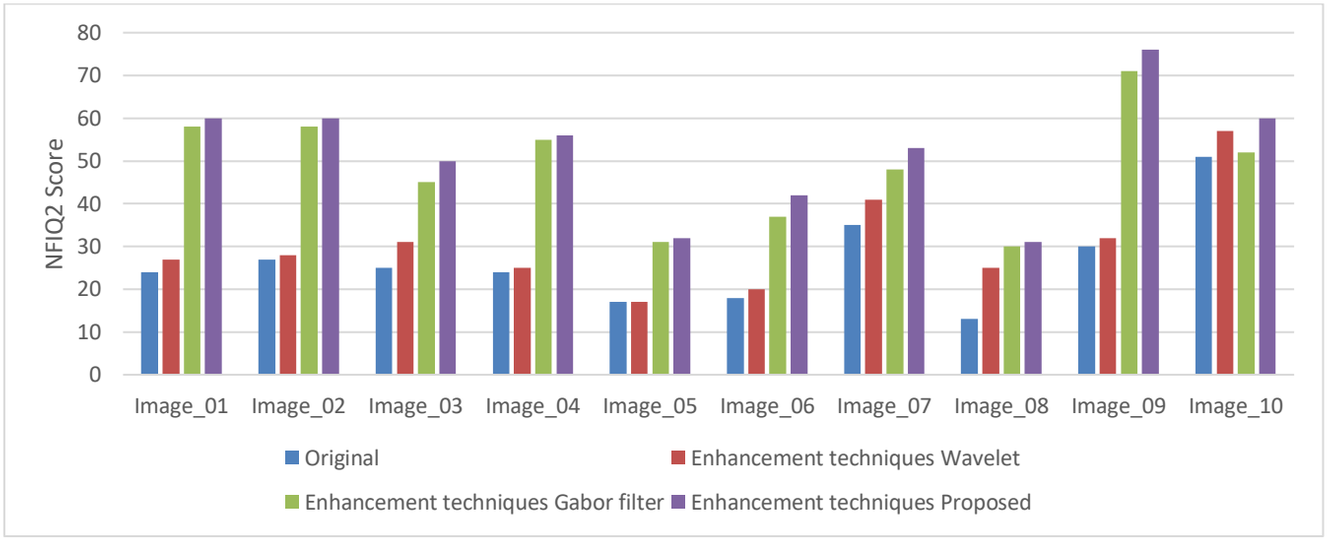

Fig.5. NFIQ2 Score Comparison of Image Enhancement Techniques Across Multiple Samples

The Proposed method consistently achieves higher scores than the other techniques in almost all cases, highlighting its superior enhancement capability and stability. While the Gabor Filter method demonstrates good results for certain images, its performance shows high variability. In contrast, the Wavelet Transform method provides only marginal improvements over the Original images. These findings confirm that the Proposed method offers significant advantages in terms of both average performance and consistency in image processing tasks.

Moreover, Fig.6. demonstrated the comparative analysis of percentage improvement achieved by each technique relative to the Original baseline reveals the superior efficacy of the Proposed method across all evaluated cases.

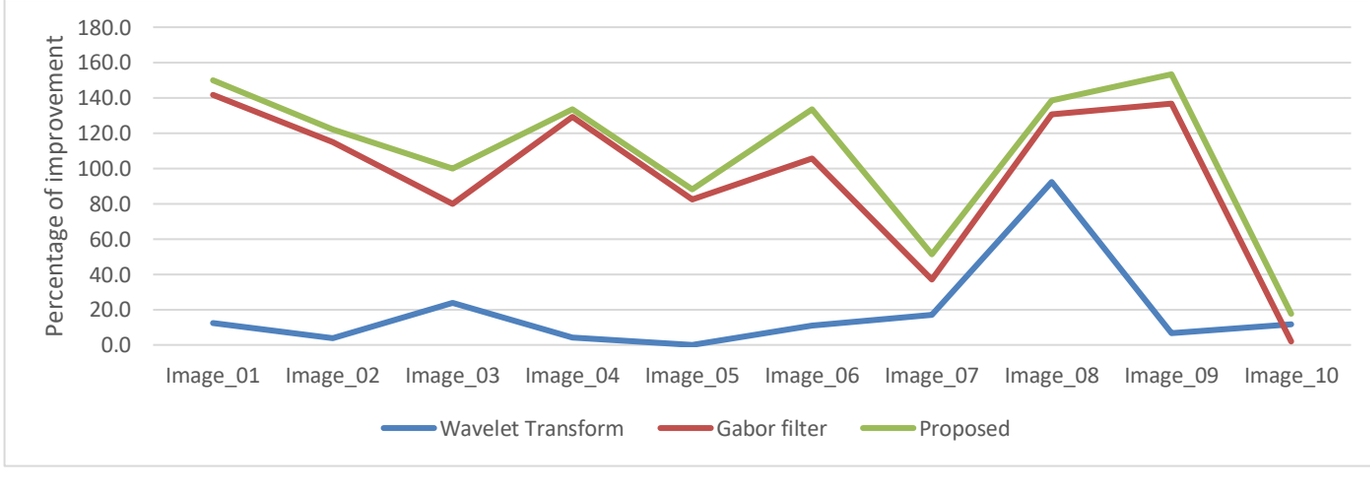

Fig.6. The comparative analysis of percentage improvement achieved by each technique.

Remarkably, the Proposed approach demonstrates substantial performance gains in critical instances such as Image_06 and Image_09, exhibiting remarkable improvements of 133.3% and 153.3%, respectively. While the Gabor filter shows significant enhancement in certain images, its performance exhibits considerable variability, as evidenced by a marginal improvement of only 2.0 % in Image_10. The Wavelet Transform, in contrast, yields only modest improvements in numerous scenarios and even results in a performance very small improve in some cases, such as Image_04. These findings collectively underscore the consistent and significantly enhanced performance offered by the Proposed method in comparison to the

standard Gabor filter and Wavelet Transform techniques. The results support the efficacy of the proposed method for improving fingerprint image quality in biometric systems.

5. Conclusion

This study proposes a fingerprint image enhancement approach that improve the Gabor filtering with the Adaptive Histogram Equalization. The experimental results demonstrate that the proposed algorithm significantly outperforms individual enhancement techniques. Specifically, fingerprint images enhanced using the proposed method achieved higher NFIQ2 scores compared to those processed using other standalone techniques, indicating superior enhancement performance. The proposed algorithm effectively reduces noise and fills in minor gaps in fingerprint images. This improvement is especially evident in images with localized blur or noise, leading to enhanced clarity and ridge-valley structure definition. Moreover, the proposed method yielded more consistent enhancement results across different samples, with less variation in quality scores.

However, this research also acknowledges certain limitations. The proposed algorithm is particularly effective for images with low contrast but may be less successful when dealing with high levels of noise or image distortion. For future work, further enhancement can be achieved by integrating multi-frequency filtering methods or advanced image restoration techniques, thereby increasing the applicability and robustness of fingerprint enhancement systems in biometric applications.

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