Comparison of the Effect of Filtering Methods on Fingerprint Accuracy Using the AFIS System on the BRAIL *Attendance Machine*

[1] Ricard Riovaldo Simatupang, Rifqi Amalya Fatekha [1], Senanjung Prayoga [1], Rifky Afriza [1]and Abdi Wijaya Sasmitha[1*]

[1]Departement of Electrical Engineering,Robotics Engineering Technology Study Program, Politeknik Negeri Batam, Batam Indonesia

[*]Email: rifqi@polibatam.ac.id

***Abstract*— Fingerprint-based attendance devices are a secure and efficient solution, but their matching performance is highly dependent on image quality. Noise caused by finger conditions and sensor limitations can reduce the accuracy of the system, so it is necessary to improve the quality of fingerprint images. This study compares four image enhancement methods, namely Gaussian, Median, Bilateral, and CLAHE filters, using two data categories to determine the most suitable method for the BRAIL laboratory attendance machine. The evaluation was based on the increase in matching confidence. The test results show that the Gaussian filter increased confidence by 23.81% in the first data category, but only 1.02% in the second data category. The Median filter produced a confidence increase of 21.37% in the first data category and the highest increase of 7.59% in the second data category. Based on these results, the Median filter produced the highest cumulative confidence due to its ability to maintain fingerprint ridge details and its resistance to noise. Therefore, the Median filter is recommended as the most effective method for improving fingerprint image quality in fingerprint-based attendance systems.**

Keyword: Fingerprint, Attendance Machine, AFIS, Median, Gaussian, Bilateral

I. Introduction

With the advancement of modern technology, fingerprint-based attendance systems are the most widely used and effective biometric solution for automating student and employee attendance records due to their practicality and high level of security. [1],[2]. Compared to traditional attendance systems that still use manual recording [1],[2],[3],[4]. BRAIL (*Barelang Robotics and Artificial Intelligence Lab*), which is a robotics laboratory, has also implemented a device called Attendance Machine, a fingerprint-based attendance system designed to improve the efficiency and effectiveness of the attendance recording process [5]. This tool is integrated with a MySQL database that stores and manages attendance data centrally, facilitating regular data monitoring and analysis [2],[6]. The fingerprint matching process is highly dependent on the image quality of the acquired fingerprint. Good image quality will facilitate the feature extraction process and improve matching accuracy during identification.

However, this system often faces obstacles due to poor fingerprint image quality, which can be caused by various factors such as noise, low contrast, uneven lighting, or suboptimal sensor quality [2]. This condition can cause misidentification (*false reject or false accept*), which can impact system performance.

To overcome this problem, image preprocessing is required to improve image quality before the matching stage is performed. One commonly used technique is the application of image filters, which serve to reduce noise, enhance contrast to improve image quality, and preserve important features such as ridges, valleys, and minutiae in fingerprint patterns [7]. This enhancement algorithm plays a crucial role in improving the quality of fingerprint images that have been degraded due to noise and other factors [8],[9]This facilitates accurate feature extraction and recognition. [10]. Thus, the matching results can be more accurate and stable. This study aims to examine and compare the effects of four types of image filters in pre-processing, namely Gaussian, Median, Bilateral, and CLAHE, on the accuracy of a fingerprint-based attendance system using AFIS (Automated Fingerprint Identification System) developed using the C# programming language with an interface in *Visual Studio 2022*. The results of this study can be used as a reference in selecting the most effective filter method to improve the performance of fingerprint identification systems for attendance applications. Thus, the developed system is capable of providing an efficient and secure attendance recording method, while overcoming the limitations of manual systems that are prone to errors and require more time [9],[11]. An attendance method that utilizes fingerprints as a unique biometric identifier that is extremely difficult to forge, thereby ensuring the authenticity and accuracy of attendance data [7],[9],[11].

II. Method

A. System AFIS Based on C#

The attendance system developed in this study uses an automatic fingerprint identification system as the primary method to ensure accurate and secure attendance. This approach significantly improves efficiency, reduces the potential for fraud, and increases the reliability of attendance records compared to traditional manual methods, which are often tedious, relatively time-consuming, and prone to errors and falsification [1],[3],[5].

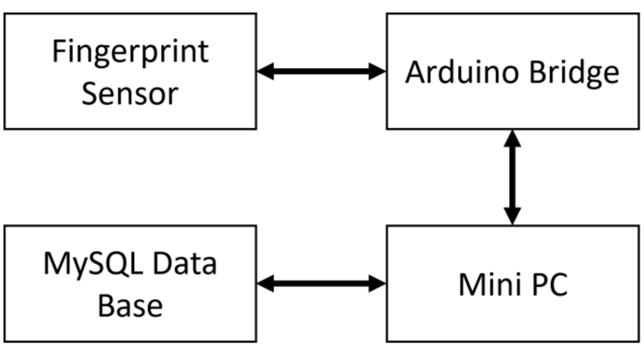


Figure 1. Diagram system pada attendance machine lab *BRAIL*.

Figure 1 shows the workflow of the attendance machine system, the fingerprint sensor captures the user's fingerprint data, which is then sent to the *Arduino Bridge* as a hardware connector. Next, the Arduino Bridge communicates with the Mini PC for data processing. The Mini PC will match and store attendance results in a MySQL database, so that attendance data can be stored and managed centrally. Biometric fingerprint recognition utilizes the unique patterns of each finger, minimizing the possibility of false attendance data and preventing identity theft [11].

This system is implemented using the C# programming language, with an interactive interface and powerful database integration such as MySQL to securely store and verify each user's unique fingerprint data.

Jain et al [2] explaining that AFIS is a widely recognized biometric method for user identification due to the unique, detailed, and durable nature of fingerprints [8], Padkan et al.[12], dan Vibert et al [13], explains that the main function of this system is to automatically identify individuals by extracting and comparing minutiae features from fingerprint images.

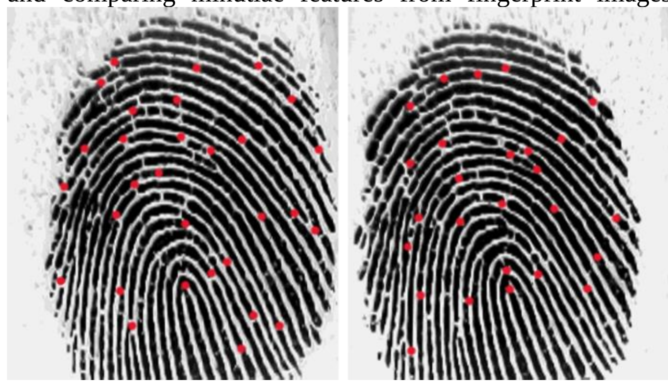


Figure 2. Image of minutiae points on fingerprints.

The red dots in *Figure 2* represent the shapes and positions of human finger minutiae. The architecture of this system utilizes an image preprocessing stage, which is a crucial step prior to the fingerprint matching process, as image quality greatly affects the recognition algorithm. During implementation, the open source AFIS library handles feature extraction and fingerprint template matching.

When the user places their finger on the sensor, the captured image will be saved in bmp format and then processed using various image enhancement filters. These filters include Gaussian, Median, Bilateral, and *Contrast Limited Adaptive Histogram Equalization* (CLAHE), each of which plays a role in reducing noise and enhancing the clarity of ridge patterns in fingerprint images [14].

CLAHE, for example, is known to improve local contrast while reducing noise, and smoothing, Gaussian can reduce noise generated by contrast enhancement [15].

After the preprocessing stage, the enhanced fingerprint image is evaluated by the Automated Fingerprint Identification System (AFIS) algorithm. This evaluation produces a matching score, typically ranging from over 40 points of confidence if the fingers are identical, which measures the similarity between the input fingerprint and the user data stored in the attendance database [16],[17]. A higher matching score indicates a higher degree of similarity [16]. This matching score is then used by the system to automatically confirm the user's identity and record their attendance in the MySQL database [18][19].

B. Image Filtering Process

To optimize fingerprint images before they are processed by AFIS, several filtering techniques are used to reduce noise, enhance contrast, and preserve the characteristic ridge-valley patterns [9]. Accurate and consistent minutiae feature extraction is highly dependent on this preprocessing step [20],[21]. This study applies and compares four main approaches to improving fingerprint image quality, namely Gaussian filter, Median filter, Bilateral filter, and CLAHE.

These four methods were chosen because each represents a different category of image filtering: Gaussian for convolution-based smoothing, which effectively reduces high-frequency noise and improves image quality [22], Median for nonlinear noise reduction [23], Bilateral for smoothing with edge preservation [23] and CLAHE for adaptive contrast enhancement.

1. Gaussian filter is a low-pass smoothing filter that reduces high-frequency noise by averaging the pixel intensity within a specified kernel. [22],[24]. Mathematically, the two-dimensional Gaussian function is defined as:

$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (1)$$

Where x and y indicate the pixel distance from the kernel center, while σ is the standard deviation that controls the smoothing level. In this study, a Gaussian filter was applied using a 5 x 5 kernel with a standard deviation (σ) of 1.0 to balance noise reduction and ridge sharpness. The selection of these parameters was based on the characteristics of fingerprint images, which have ridge patterns with medium spatial frequencies. A medium-sized kernel is effective in reducing random noise without causing excessive blurring, while a relatively small (σ) value preserves the sharpness of the ridge structure. This parameter is selected to achieve an optimal balance between noise reduction and ridge detail preservation. Although effective in reducing random noise, excessive smoothing can cause ridge edges to become blurred, potentially reducing the sharpness of minutiae features [15].

2. Median filter works by replacing the intensity of each pixel with the median value of the surrounding pixels in a specified window (kernel). Unlike linear filters such as Gaussian filters, median filters are non-linear filters that are very effective at removing salt-and-pepper noise without blurring edges. Mathematically, the output value of the median filter can be expressed as:

$$g(x, y) = median\{f(s,t)| \in S_{x,y} \quad (2)$$

Where $f(s,t)$ represents the pixel intensity in the local window $S_{x,y}$, and $g(x,y)$ is the result of filtering the center pixel. In this study, the median filter was applied using a 3 x 3 kernel, which provided an optimal balance between noise removal and ridge-valley structure preservation. This property is very useful for preserving the fine details of ridge patterns in fingerprint images [14].

3. Bilateral filters operate by adjusting the intensity of each pixel based on the values of its neighboring pixels, where each output value is the median of the set of intensities around the central pixel. This non-linear approach has proven to be very effective in removing *salt-and-pepper* noise while preserving image edge details.
Mathematically, the median filter process can be expressed as:

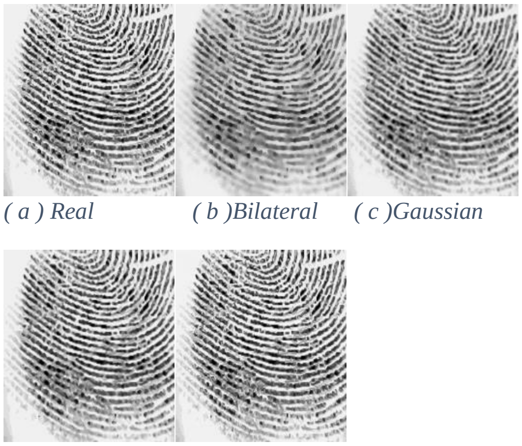
$$\mathrm{BF[I]}_{p} = \frac{1}{W_p} \sum_{q \epsilon S} G_{\sigma_s}\left(\left||p-q|\right|\right) G_{\sigma_r}\left(\left|I_P - I_q\right|\right) I_q \quad (3)$$

Where G_{σ_s} is a spatial Gaussian function that measures the proximity of positions between pixels, G_{σ_r} is a radiometric Gaussian function that measures the similarity of intensities between pixels, and W_p is a normalization factor. This filter effectively reduces noise without blurring *ridge* boundaries, allowing *ridge-valley* structures to be clearly preserved.

In this study, the parameters used include a kernel diameter of 9 pixels and spatial deviation. (σ_s) and intensity deviation (σ_r) are each set at 75, which is selected to maintain a balance between smoothing and preserving edge details. The selection of a kernel diameter of 9 pixels and values of (σ_s) and (σ_r) of 75 was done empirically based on preliminary testing and literature references. These parameters were chosen because they provide a balance between image smoothing and edge detail preservation. This method has been proven to improve *ridge* pattern clarity without causing halo artifacts that often appear in conventional edge enhancement methods. [22].

4. CLAHE technique works by enhancing the local contrast of an image by dividing it into several blocks (or tiles) and performing adaptive histogram equalization on each block. To prevent excessive noise amplification, a clip limit mechanism of 2.0 and a tile size of 8×8 used. Several parameter combinations have been tested, and these values produce the best visual quality on the research dataset. CLAHE is very useful for fingerprint images with uneven illumination or low contrast, as it can improve *ridge* clarity across the entire image area uniformly [15].

Each filtering method is applied individually to the identical fingerprint image dataset before feature extraction and matching using the AFIS system. This stage aims to evaluate the effectiveness of each filter in improving image quality. Given that the performance of this recognition algorithm is highly vulnerable and influenced by image quality, especially for images with high noise levels, low contrast, or uneven textures due to finger pressure or sensor conditions. Therefore, efficient enhancement is crucial, especially for poor-quality images [15]. The filtered image is then evaluated based on recognition accuracy and similarity scores generated in the fingerprint-based attendance system [25]. To provide a clearer picture or illustrate the stages of applying each filtering method, Figure 3 on the next page shows the results of processing the original fingerprint image, which is then processed again using four image enhancement techniques. image enhancement techniques as proposed in this discussion, each with its own purpose and uniqueness, namely: Gaussian, Median, Bilateral, and CLAHE.



(a) Real (b)Bilateral (c)Gaussian

(d) Median (e)CLAHE

Figure 3. Images processed using various filters (a. Original Image, b. Bilateral, c. Gaussian, d. Median, e. CLAHE)

Figure 3 shows the differences in the results of the filtering process with the aim of improving the quality of fingerprint images using several filtering methods. Visually, the original image (*Fig 3. a*) still contains noise and has low contrast, so that the ridge and valley patterns are not clearly visible. After applying the filter, it can be seen that:

- Bilateral filter (Fig 3. b) It can reduce noise while maintaining edge details, but the results tend to be blurrier or less clear, especially in areas with fine textures.
- Gaussian filter (Fig 3. c) produces a good smoothing effect while eliminating high-frequency noise, but slightly reduces the sharpness of ridge patterns.
- Median filter (Fig 3. d) effective in removing impulse noise without blurring fingerprint patterns, so that ridge lines appear more consistent compared to images produced by Gaussian filters.
- CLAHE (Fig 3. e) significantly increases the contrast of the image, producing more prominent *ridge* patterns, but can cause increased noise in certain areas.

Overall, the most notable difference between the results of the filters is in the smoothness of the texture and sharpness of the ridge patterns. The Median and Gaussian filters provide the best balance by reducing noise while maintaining the details of the fingerprint patterns, such as the ridge structures, thereby producing a more stable image for the matching process. The next section will detail the experimental setup, present the results of this comparative analysis, and discuss the implications of each filter's performance on the overall accuracy of AFIS. Testing will be conducted by dividing the data into two categories: the first category will consist of data with an initial confidence value below 40, and the second category will consist of data with confidence value above 40 points.

III. RESULTS AND DISCUSSION

This study used 40 sets of fingerprint data, which were then divided into two categories based on the initial confidence level where the images had not been filtered:

1. Low- confidence data (< 50 point)
2. High- confidence data (> 50 point)

With a minimum limit of 40 points for identical fingers. Objective the division is to see how various images affect the confidence of the AFIS system in both data conditions.

A. Testing and evaluation of low- confidence data (<50 points)

Testing on 20 low- confidence data sets showed that the application of image filters had a significant impact on AFIS accuracy, thereby helping to identify the most effective filters for low-quality data.

TABLE I

FILTER MATCHING SCORES LOW CONFIDENCE DATA

Name	Original	Median	Gaussian	CLAHE	Bilateral
Abdi wijaya	41.89	78.47	76.06	56.02	76.22
Bernard Sitio	41.24	42.64	59.7	52.77	36.64
Boby	36.62	36.93	46.20	38.10	29.81
Erik	30.78	31.92	49.81	44.53	48.93
Eza	37.53	38.35	39.38	37.53	37.87
Jossua Hotua	36.87	40.68	37.87	36.46	29.35
Marel	47.19	51.72	78.19	50.52	65.81
Pilo	28.17	31.42	31.5	27.9	30.08
Revino	44.25	47.87	47.63	46.45	32.29
Ricard	36.58	60.71	53.42	33.88	47.31
Riovaldo	39.43	42.43	48.27	42.43	38.40
Rio	43.69	51.81	49.61	43.63	45.08
Sasmitha	30.62	56.29	62.46	34.26	52.43
Elwin Silalahi	40.99	55.74	68.57	38.05	65.73
Timothy Nico	49.78	54.32	74.29	59.44	40.09
Rey Rizky	49.80	67.95	51.84	51.21	37.71
Delon	44.74	44.58	45.49	43.82	37.56
Arifin	33.52	55.06	29.95	30.48	45.44
Roger Siregar	40.59	45.19	29.77	41.42	22.32
Beni Candra	24.73	41.24	34.36	27.98	16.25

Table I presents the results for 20 test data sets in the first data category, where the confidence value of the initial image without filters shows a low range of 20 to 50 points.

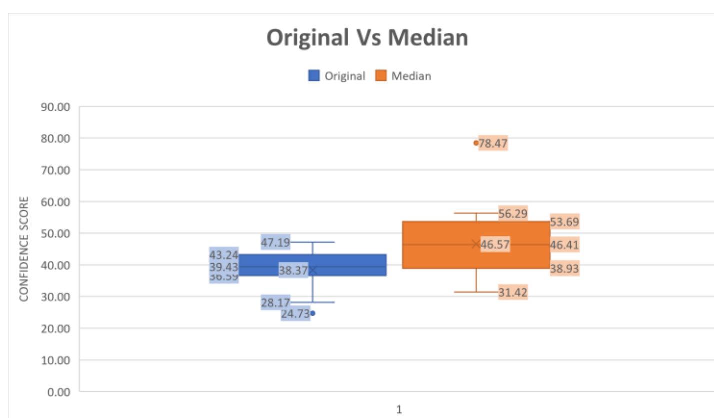


Figure 4. Median vs original confidence comparison chart

Figure 4 shows a comparison of confidence values between the original image and the image resulting from Median filtering on category 1 data (low-confidence data) consisting of 20 test data points. The test results show that Median filtering produces higher confidence values than the original image. Median filtering shows a significant improvement, marked by higher median and maximum values and a wider distribution range compared to the original image.

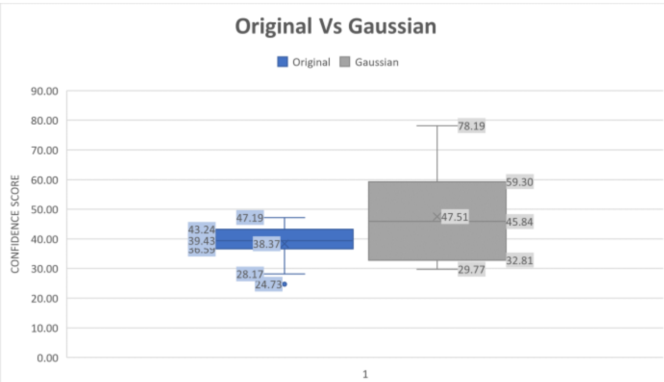


Figure 5. Gaussian vs original confidence comparison chart

. Figure 5 shows a comparison of confidence values between the original image and the Gaussian-filtered image in category 1 data (low-confidence data). The Gaussian filter shows an increase in median and maximum confidence values compared to the original image, although with a more varied data distribution based on the box-and-whisker plot.

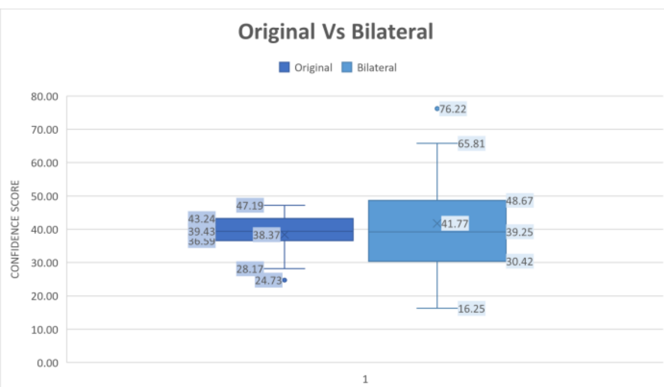


Figure 6. Bilateral vs original confidence comparison chart < 50 Point

Figure 6 compares the confidence values between the original image and the image processed using a bilateral filter across 20 data samples. Overall, the bilateral filter demonstrates an increase in confidence compared to the original image. However, this improvement is not consistent, as several data points exhibit a decrease in confidence, indicating unstable performance.

For the first data category (low-confidence data), visual analysis of the graph shows that the most prominent confidence improvement occurs with the Gaussian filter, particularly at the sixth data point. The observed fluctuations in confidence values indicate that each filtering method responds differently to the characteristics of the input data at each test instance. Consequently, this study does not aim to achieve perfectly constant confidence values, but rather evaluates filter performance based on the overall stability of confidence changes.

When overall performance stability is assessed by considering both the magnitude of confidence improvement and the occurrence of minimal decreases, the median filter demonstrates the most consistent and reliable performance compared to the other evaluated filters..

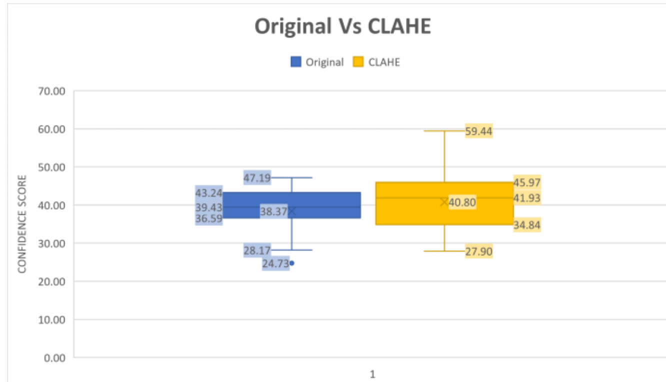


Figure 7. CLAHE vs original confidence comparison chart

Figure 7 compares the confidence values between the original image and the image processed using CLAHE on 20 data samples. Overall, CLAHE produces an increase in confidence at several data points; however, its performance is not entirely stable, as a decrease in confidence is also observed at certain points. Compared to the bilateral filter, the range of confidence values obtained using CLAHE is narrower, indicating more limited performance variation.

B. Testing and evaluation of high- confidence data (50 points)

The test was conducted on 20 data sets with a high confidence level to determine the effect of image filters on data that already has good quality, particularly in maintaining the performance of the AFIS system.

TABLE II
FILTER MATCHING SCORES HIGH- CONFIDENCE

Name	Original	Median	Gaussian	CLAHE	Bilateral
Aldi	89.4	83.6	61.3	91.1	46.0
Bambang	97.9	118.9	121.2	101.2	95.5
Bintang	72.3	62.8	73.0	67.6	16.6
Daffa Lisfatia	135.2	141.6	154.3	135.3	142.8
Fitrah	83.2	104.2	95.9	79.8	40.5
Olivia	67.1	77.4	73.7	67.3	47.9
Piulina	54.7	52.8	43.9	54.6	28.3
Reyendra	68.3	71.1	70.3	65.4	56.9
Ricard 1	99.5	119.4	95.3	99.5	78.6
Vino	87.4	91.7	87.4	88.6	78.1
Viona Harefa	68.4	71.4	78.4	68.5	76.2
Zainul Daffa	100.3	107.7	105.6	100.7	100.8
Sinurat	61.5	69.3	71.4	41.4	62.5
Arya	81.7	96.1	76.5	88.3	83.5
Yudha	58.2	59.6	46.9	59.0	37.9
Beny	71.9	72.2	75.4	71.9	81.3
Harahap	79.4	90.2	87.9	79.4	84.1
Muh Daffa	61.8	71.2	74.6	62.8	45.0
Marolop	51.9	54.6	57.2	63.4	41.6
Bosum	60.0	60.2	31.3	62.2	19.0

Table II presents the results for the second data category, which consists of samples with initial confidence values exceeding 50 points. For these high-quality fingerprint images, the application of image enhancement filters produced varying effects, demonstrating how each filter affects data that already has good matching quality. This evaluation aims to assess whether the applied filters are able to maintain the existing data quality without compromising AFIS performance, while still showing patterns consistent with those observed in the first data category.

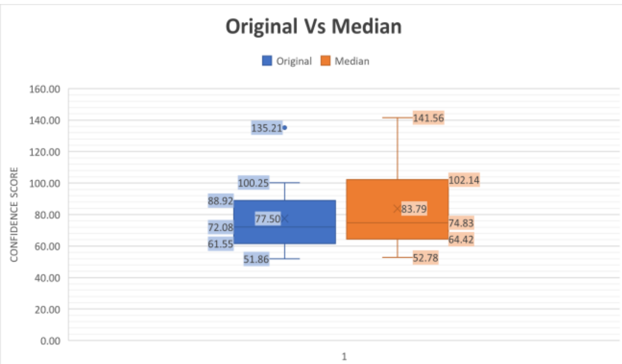


Figure 8. Median vs original confidence chart > 50 Point

Figure 8 presents a comparison of confidence values between the original image and the image processed using a median filter for the second data category, which consists of data with high confidence (good quality). Based on the plot, the median filter does not produce a substantial increase in confidence compared to the original image. Some decreases in confidence are also observed at certain data points. This shows that for data that already has good initial quality, the application of a median filter tends to maintain the existing confidence level rather than increase it significantly, while avoiding excessive matching performance degradation.

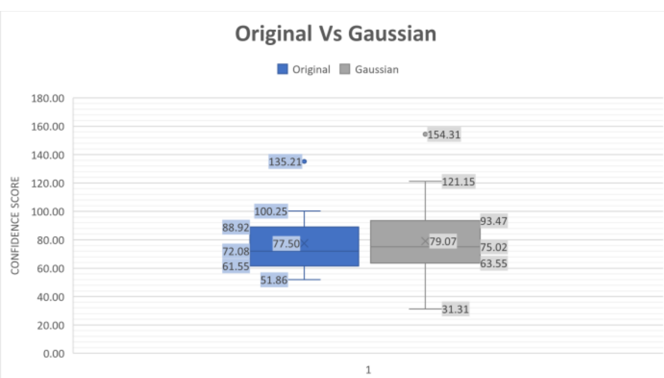


Figure 9. Gaussian vs original confidence chart > 50 Point

Figure 9 compares the confidence values between the original image and the Gaussian-filtered image for the second data category. The results show no significant difference, indicating that the Gaussian filter generally maintains the confidence level in data with high confidence with only slight variation.

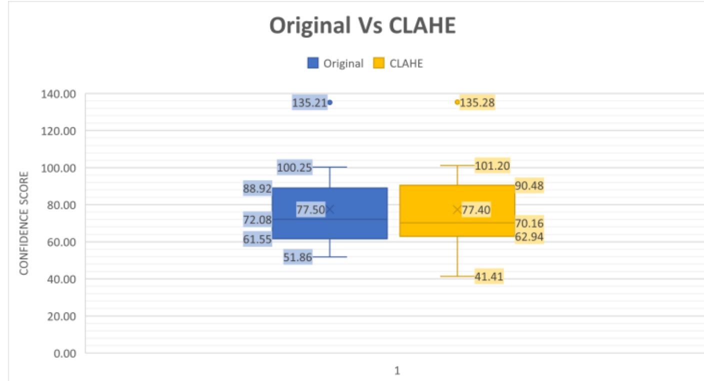


Figure 10. CLAHE vs original confidence chart > 50 Point

Figure 10 Shows that the CLAHE filter results are generally comparable to the original image results; however, some loss of confidence can be observed, as shown in the graph. This indicates that although CLAHE does not significantly improve data with high confidence, this filter can cause minor degradation in certain samples when applied to images that already have good quality.

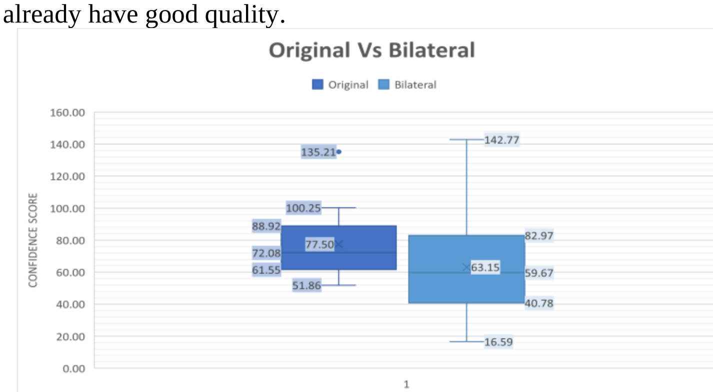


Figure 11. Bilateral vs original confidence chart > 50 Point

Figure 11 presents the comparison results obtained using bilateral filters for the second data category (high confidence data). Based on the box and whisker plot, the bilateral filter shows a higher upper whisker compared to the original image, indicating that some samples experienced an increase in confidence values. However, the median and interquartile range of the bilateral filter results are lower than the original image, and the lower whisker extends further down, reflecting a more pronounced reduction in confidence at certain data points.
Overall, although bilateral filters provide improvements for some samples, they also cause greater confidence reductions, resulting in less stable performance for data with high confidence. In contrast, the median filter exhibits more reliable behavior by providing relatively stable improvements with smaller confidence reductions. Although all filters show some confidence reduction at certain data points, the reduction from the median filter is relatively minimal, while the Gaussian filter shows a more noticeable reduction and CLAHE performs similarly to unfiltered data with some reduction. Therefore, bilateral filters are less suitable for data with high confidence.

C. *Average Performance and Improvement Percentage*

From the test results conducted on both categories using 40 fingerprint image samples, the following averages were obtained:

TABLE III
LOW- CONFIDENCE CATEGORY AVERAGE SCORE

Filter	Average
Original	38.37
Median	46.57
Gaussian	47.51
CLAHE	40.80
Bilateral	41.77

TABLE IV
HIGH- CONFIDENCE CATEGORY AVERAGE SCORE

Filter	Average
Original	77.505
Median	83.795
Gaussian	79.071
CLAHE	77.403
Bilateral	63.145

Based on the average values obtained, the percentage increase produced by each filter method was then calculated using the following formula:

$$\%\, improvement = \frac{(Filter\ value - Original\ value)}{Original\ value} \times 100\% \qquad (4)$$

The results of the percentage increase calculation for each filter in the low confidence category are shown in Table V below:

TABLE V
IMPROVEMENT PERCENTAGE FOR LOW-CONFIDENCE CATEGORY

Filter	*%Improvement*
Median	+21.37%
Gaussian	+23.81%
CLAHE	+6.32%
Bilateral	+8.85%

TABLE IVI
IMPROVEMENT PERCENTAGE FOR HIGH-CONFIDENCE CATEGORY

Filter	*%Improvement*
Median	+7.59%
Gaussian	+1.02%
CLAHE	−0.13%
Bilateral	−18.53%

Based on the average filter effect table, the median filter provides the best performance in both data categories, with a significant improvement in both categories. To provide further visualization of the average rate data, it is then visualized in graph form as shown in Figure 12 and Figure 13.

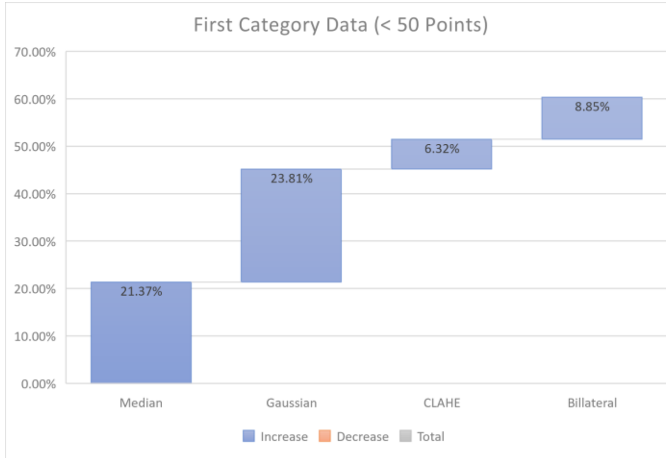


Figure 12. Improvement Graph Low-Confidence Category

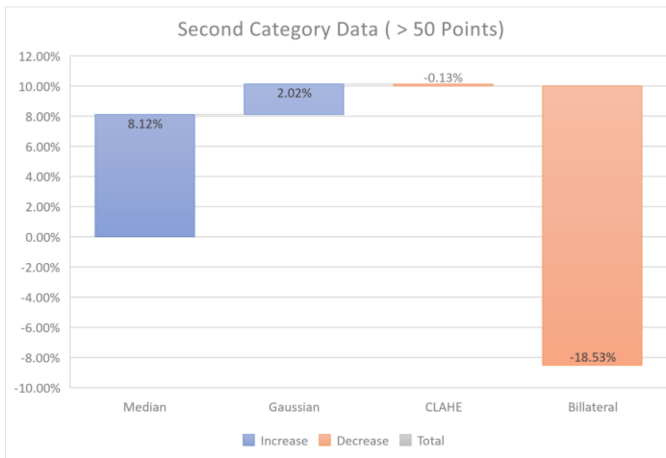


Figure 13.Improvement Graph High- Confidence *Category*

Based on the calculation results, the Gaussian filter provides the highest confidence improvement in the first category of data, with an increase of 23.81% compared to the original image. In the second data category with > 50 points, the median filter provides the highest increase of 7.59% compared to the original image, and the bilateral filter provides the most significant decrease in the second data category > 50 of 18.53%, as visualized in Figure 13. Confidence

IV. CONCLUSION

Based on the results of calculating the average value and percentage increase in confidence, the Gaussian filter provides the highest performance improvement in the first data category (low-confidence data), with an increase of 23.81% compared to the original image. This shows that the Gaussian filter is effective in improving the quality of fingerprint images with a low initial confidence level.However, when viewed as a whole across both data categories, the Median filter shows the most optimal performance. This filter produces the highest cumulative confidence increase and is able to maintain image quality in data with already good confidence levels. Compared to other methods, the Median filter outperforms the Gaussian filter by 2.27%, the CLAHE filter by 9.65%, and the Bilateral filter by 73.06%. Therefore, the Median filter is recommended as the most effective filtering method to improve fingerprint matching performance in this study.However, further research is still needed to optimize filtering parameters, combine several image enhancement methods, and integrate deep learning-based approaches to improve image clarity and system robustness against variations in lighting conditions and noise. In addition, testing on larger and more diverse datasets is also needed so that the performance of the AFIS system can be more consistent under various conditions.

REFERENCES.

[1] D. Feng, P. Wang, and L. Zu, "Design of Attendance Checking Management System for College Classroom Students Based on Fingerprint Recognition," in *2020 Chinese Control And Decision Conference (CCDC)*, IEEE, Aug. 2020, pp. 555–559. doi: 10.1109/CCDC49329.2020.9164638.

[2] A. K. Jain, D. Deb, and J. J. Engelsma, "Biometrics: Trust, But Verify," *IEEE Trans Biom Behav Identity Sci*, vol. 4, no. 3, pp. 303–323, Jul. 2022, doi: 10.1109/TBIOM.2021.3115465.

[3] S. J, "Smart attendance monitoring system using multimodal biometrics," *Sigma Journal of Engineering and Natural Sciences – Sigma Mühendislik ve Fen Bilimleri Dergisi*, pp. 168–188, 2025, doi: 10.14744/sigma.2024.00030.

[4] S. Z. Sweidan, S. M. Alshareef, and K. A. Darabkh, "SATA: A New Students Attendance Tracking Application," in *2021 9th International Conference on Information and Education Technology (ICIET)*, IEEE, Mar. 2021, pp. 41–46. doi: 10.1109/ICIET51873.2021.9419593.

[5] A. Mishra, R. Kamble, V. Pare, and R. Sahu, "Multimodal Biometric Attendance System," *SSRN Electronic Journal*, 2020, doi: 10.2139/ssrn.3568531.

[6] H. Shams, T. Jan, A. A. Khalil, N. Ahmad, A. Munir, and R. A. Khalil, "Fingerprint image enhancement using multiple filters," *PeerJ Comput Sci*, vol. 9, p. e1183, Jan. 2023, doi: 10.7717/peerj-cs.1183.

[7] S. Al Amin, Md. A. Islam, and Md. S. Islam, "A Fingerprint Based Smart Attendance and Security System Using IoT and Ultrasonic Sensor," in *2021 International Conference on Automation, Control and Mechatronics for Industry 4.0 (ACMI)*, IEEE, Jul. 2021, pp. 1–5. doi: 10.1109/ACMI53878.2021.9528092.

[8] H. Kolivand, A. A. B. A. Hamid, S. Asadianfam, and M. S. M. Rahim, "A functional enhancement on scarred fingerprint using sigmoid filtering," *Neural Comput Appl*, vol. 34, no. 22, pp. 19973–19994, Nov. 2022, doi: 10.1007/s00521-022-07520-x.

[9] B. Y. Satria, A. Bejo, and R. Hidayat, "Fingerprint Enhancement using Iterative Contextual Filtering for Fingerprint Matching," in *2021 9th International Conference on Information and Communication Technology (ICoICT)*, IEEE, Aug. 2021, pp. 186–191. doi: 10.1109/ICoICT52021.2021.9527482.

[10] V. A. Baboshina, A. R. Orazaev, E. D. Shalugin, and A. M. Sinitca, "Combined Use of a Bilateral and Median Filter to Suppress Gaussian Noise in Images," in *2022 11th Mediterranean Conference on Embedded Computing (MECO)*, IEEE, Jun. 2022, pp. 1–5. doi: 10.1109/MECO55406.2022.9797124.

[11] L Karthik Narayan, Sonu. G, and Soukhya S. M, "Fingerprint Recognition and its Advanced Features," *International Journal of Engineering Research and*, vol. V9, no. 04, Apr. 2020, doi: 10.17577/IJERTV9IS040393.

[12] N. Padkan, B. S. Bigham, and M. R. Faraji, "Fingerprint matching using the onion peeling approach and turning function," *Gene Expression Patterns*, vol. 47, p. 119299, Mar. 2023, doi: 10.1016/j.gep.2022.119299.

[13] B. Vibert, J.-M. Le Bars, C. Charrier, and C. Rosenberger, "Comparative study of minutiae selection methods for digital fingerprints," *Front Big Data*, vol. 6, Apr. 2023, doi: 10.3389/fdata.2023.1146034.

[14] H. Kolivand, A. A. B. A. Hamid, S. Asadianfam, and M. S. M. Rahim, "A functional enhancement on scarred fingerprint using sigmoid filtering," *Neural Comput Appl*, vol. 34, no. 22, pp. 19973–19994, Nov. 2022, doi: 10.1007/s00521-022-07520-x.

[15] R. P. Sharma and S. Dey, "Two-stage quality adaptive fingerprint image enhancement using Fuzzy C-means clustering based fingerprint quality analysis," *Image Vis Comput*, vol. 83–84, pp. 1–16, Mar. 2019, doi: 10.1016/j.imavis.2019.02.006.

[16] N. Padkan, B. S. Bigham, and M. R. Faraji, "Fingerprint matching using the onion peeling approach and turning function," *Gene Expression Patterns*, vol. 47, p. 119299, Mar. 2023, doi: 10.1016/j.gep.2022.119299.

[17] H. Choi, S. S. Woo, and H. Kim, "Blind-Touch: Homomorphic Encryption-Based Distributed Neural Network Inference for Privacy-Preserving Fingerprint Authentication," *Proceedings of the AAAI Conference on Artificial Intelligence*, vol. 38, no. 20, pp. 21976–21985, Mar. 2024, doi: 10.1609/aaai.v38i20.30200.

[18] M. Aritonang, I. D. Hutahaean, H. Sipayung, and I. H. Tambunan, "Implementation of Fingerprint Recognition Using Convolutional Neural Network and RFID Authentication Protocol on Attendance Machine," in *Proceedings of the 2020 10th International Conference on Biomedical Engineering and Technology*, New York, NY, USA: ACM, Sep. 2020, pp. 151–156. doi: 10.1145/3397391.3397449.

[19] K. Bhagat, S. Ghorpade, G. Patil, Y. Kamble, and D. A. Bhosale, "Lab Attendance Using Fingerprint Sensor," *Int J Res Appl Sci Eng Technol*, vol. 10, no. 4, pp. 1704–1707, Apr. 2022, doi: 10.22214/ijraset.2022.41517.

[20] J. Wieditz, Y. Pokern, D. Schuhmacher, and S. Huckemann, "Characteristic and Necessary Minutiae in Fingerprints," *J R Stat Soc Ser C Appl Stat*, vol. 71, no. 1, pp. 27–50, Jan. 2022, doi: 10.1111/rssc.12520.

[21] A. Sengupta and A. Anshul, "Secure hardware IP of GLRT cascade using color interval graph based embedded fingerprint for ECG detector," *Sci Rep*, vol. 14, no. 1, p. 13250, Jun. 2024, doi: 10.1038/s41598-024-63533-7.

[22] E. O. Rybakova, E. E. Limonova, and D. P. Nikolaev, "Fast Gaussian Filter Approximations Comparison on SIMD Computing Platforms," *Applied Sciences*, vol. 14, no. 11, p. 4664, May 2024, doi: 10.3390/app14114664.

[23] M. F. Alamsyah, L. S. Harahap, and M. Firjatullah, "Meningkatkan Kualitas Gambar Digital melalui Pengurangan Noise Menggunakan Median Filtering," *Data Sciences Indonesia (DSI)*, vol. 5, no. 1, pp. 96–104, Jul. 2025, doi: 10.47709/dsi.v5i1.6290.

[24] V. A. Baboshina, A. R. Orazaev, E. D. Shalugin, and A. M. Sinitca, "Combined Use of a Bilateral and Median Filter to Suppress Gaussian Noise in Images," in *2022 11th Mediterranean Conference on Embedded Computing (MECO)*, IEEE, Jun. 2022, pp. 1–5. doi: 10.1109/MECO55406.2022.9797124.

[25] S. Sreehari, P. D. Dilavar, S. M. Anzar, A. Panthakkan, and S. A. Amin, "Performance Evaluation of Image Enhancement Techniques on Transfer Learning for Touchless Fingerprint Recognition," in *2024 7th International Conference on Signal Processing and Information Security (ICSPIS)*, IEEE, Nov. 2024, pp. 1–6. doi: 10.1109/ICSPIS63676.2024.10812653.