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Performance Evaluation of CLAHE-Enhanced Edge Detection on Low-Light Faces

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***Abstract* — Edge detection is an important early stage in an image processing-based face detection system. However, the quality of edge detection is highly dependent on the lighting and contrast of the input image. A common problem is the low contrast quality of facial images, which causes edge detection results to be suboptimal, especially in low-light images. This study evaluates the effect of the use of the Contrast Limited Adaptive Histogram Equalization (CLAHE) method on edge detection performance using Canny operators. Two scenarios were tested: edge detection without preprocessing and edge detection after image processing with CLAHE. Evaluation was carried out using two metrics: the number of contours and the total area of the contours of the detected results. The test results showed that the use of CLAHE consistently increased the number of contours and stabilized the contour area distribution, indicating an increased sensitivity to facial edge details. Although an increase in the number of contours can increase the risk of noise detection, the results suggest that CLAHE is able to clarify facial structures that were previously uncaptured. CLAHE has proven to be effective as an image enhancement method in edge detection-based facial detection systems.**

Keywords—CLAHE, Canny, Detection, Edge, Image

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I. INTRODUCTION

Human facial imagery plays a crucial role in various biometric recognition systems, cybersecurity, as well as artificial intelligence (AI)-based intelligent applications [1] [2]. Facial identification is not only used in consumer devices such as smartphones and surveillance cameras, but also in national security systems, behavioral analysis, and tracking of individuals in public settings. Image processing is one of the fields that is currently being researched such as the use of the CNN model [3] with a wide range of architectural models [4] on various data such as script images [5] and the image of the priest [6]. However, sub-optimal lighting quality is often a major challenge in producing reliable facial imagery for further analysis. One of the most difficult conditions in facial image acquisition is low lighting. In this situation, the image tends to lose contrast, the details of the facial structure are blurred, and the noise increases significantly. Low-light imagery is often not informative enough to be used in the process of identifying, segmenting, or extracting features, which are crucial stages in the image processing pipeline. Therefore, an approach is needed that is able to improve the visual quality of the image without damaging the important details required by the analysis algorithm.

Poor light conditions cause the facial structure to become less visible. This has a direct impact on the performance of various stages of image processing, especially in the edge detection process which functions to extract important boundaries and contours in the image. Edge detection is a crucial stage because the results greatly determine the quality of segmentation and feature extraction required in advanced processes, such as facial recognition, expression classification, and face tracking. In dealing with the problem of low lighting, one of the widely used image enhancement methods is Contrast Limited Adaptive Histogram Equalization (CLAHE). This method locally enhances the contrast of the image by avoiding excessive noise enhancement through clip limit restriction. In other words, CLAHE is able to clarify local details in the image, especially in dark areas, without causing over sharpening or extreme noise. The integration of CLAHE as a pre-processing stage is expected to improve edge detection performance by resulting in sharper contrast and clearer object boundaries.

However, there are still few studies that explicitly evaluate the impact of CLAHE on the performance of various edge detection algorithms in the context of low-light facial imagery. Therefore, it is important to conduct comprehensive testing of edge detection methods such as Sobel, Prewitt, Canny, and others, either without or with CLAHE enhancements. This study aims to compare the edge detection performance in the two conditions using three main evaluation parameters, namely the number of contours detected by calculating the number of contours that are successfully identified by the edge detection algorithm, which reflects the sensitivity of the method to visual details in the image. Next, the total area of the contour is assessed by assessing the area of the detected contours, which gives an idea of how much of the facial structure has been successfully reconstructed by the method. Visualization of edge detection results through visual representation, subjective assessment is carried out on the sharpness, clarity, and completeness of the facial structure produced after the edge detection process. This includes the appearance of important elements such as eyes, nose, lips, and facial lines. With this approach, the study not only evaluates the numerical performance of the algorithm, but also provides a holistic view of the impact of CLAHE on the visual quality of edge detection results. It is hoped that the results of this study can provide new insights in the development of a more robust facial image processing system against poor lighting, as well as a reference in the selection of optimal pre-processing and edge detection techniques for real-world applications such as night surveillance, automatic door security systems, and other computer vision-based devices.

To map the position of this research in the current research landscape, a literature study has been conducted on a number of relevant studies. Research by Zhang shows that the use of the Canny method on low-light imagery without image enhancement tends to fail to extract subtle facial details [7]. Meanwhile, Wang and Liu's research integrated conventional equalization histograms before edge detection, but faced the obstacle of increased noise [8]. Other studies have shown that CLAHE is superior to other contrast-enhancing methods in maintaining facial morphological details [9].

Comparative study of Canny Sobel and Prewitt's performance on facial imagery with each advantage of each method [10]. In another study with auto-adjusted CLAHE, the contour area increased by 30%, and the contour area rose by 20%, the edge detection was 40% sharper [11]. The use of CLAHE before Prewitt and Roberts. The number of contours increased by 18%, the total area was greater by 12%, with more comprehensive visualization of facial contours [12]. Qualitative assessment shows excellent performance of CLAHE [13] and showcasing enhanced images with better contrast, clearer details, and less time consumption [14]. This study discusses how various edge detection methods, including Roberts, Prewitt, Sobel, and Canny, work, with the latter highlighted for their superior ability to minimize errors and provide accurate edge detection results [15] [16].

These findings suggest that although CLAHE has been widely used for image enhancement and edge detection has been extensively explored, the combination of the two with a thorough evaluation of the number of contours, total contour area, and systematic visualization of edge detection results on low-light facial images has not been widely explored. Therefore, this study is designed to fill these gaps, with the aim of evaluating and comparing the performance of various edge detection algorithms before and after the implementation of CLAHE, using quantitative and visual approaches simultaneously.

II. METHODOLOGY

The following are the stages of the research methodology shown in the Fig *1*.

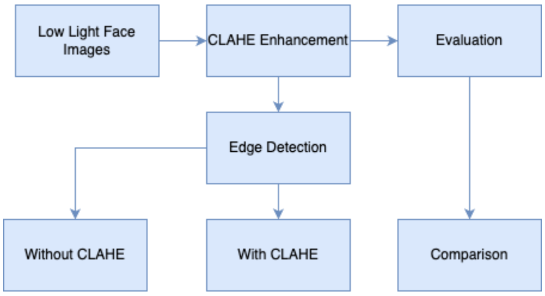

Fig 1. Methodology

The data used in the image data that has less lighting will be compared with the CLAHE technique and without CLAHE to be able to identify the influence of CLAHE on the image results. The measure used was to compare the effect of CLAHE on edge detection quality visually and statistically with two alternative approaches with the number of contours detected, total contour area and visualization of edge detection results.

III. RESULT AND DISCUSSION

This study uses the Face Detection dataset in the form of publicly available data with 1300 image. This dataset consists of a collection of images of human faces taken in a variety of conditions and backgrounds, making them representative for face detection experiments, especially under varying lighting conditions. Sample data is shown in Fig *2* dan Fig *3*.

Fig 2. Sample Image 1

Fig 3. Sample Image

Data Quantity and Characteristics

In total, this dataset contains more than 6,000 images of diverse faces, both in terms of age, expression, pose, and environmental background. The images have varying resolutions, but generally range in average size of 896 × 896 pixels. This variation in size presents its own challenges in the preprocessing and segmentation process, as not all images have uniform proportions.

Lighting Conditions

Although not explicitly categorized in the lighting labels, visual observations of the contents of the dataset showed that some of the images were in low-light conditions, others in normal lighting, and a small portion were overexposed. These lighting conditions affect the clarity of facial features such as eyes, nose, and mouth, which play an important role in the process of edge detection and contour extraction.

Data Format and Distribution

All images in the dataset are stored in JPEG (.jpg) format with RGB (Red, Green, Blue) color quality. Distributionally, the images are fairly evenly distributed in terms of facial poses (frontal and semi-profile), but there are no specific bounding box annotations or lighting labels available. Therefore, the analysis was carried out with a visual and experimental approach, mainly to identify the edge detection performance against exposure variations.

Pre-processing stage

Before applying the edge detection algorithm, each image goes through several preprocessing stages as follows:

Resize

To maintain consistency in processing and speed up calculations, the entire image is resized to fixed dimensions (e.g. 512 × 512 pixels), without drastically changing the aspect ratio.

Grayscale Conversion

RGB color images are converted to grayscale imagery to focus analysis on light intensity without being affected by color variation. This is essential because the majority of edge detection algorithms, such as Sobel and Canny, work optimally on images with a single color channel.

Normalization of Intensity

The pixel intensity value is normalized to a specific range (typically 0–255 or 0–1) to ensure the stability of the value distribution before and after the contrast enhancement process.

Separation of Datasets by CLAHE Treatment

After basic preprocessing, the dataset is divided into two groups:

Group Without CLAHE

Images are directly processed using the edge detection method without contrast modification.

Group With CLAHE

The image was first enhanced in contrast using the Contrast Limited Adaptive Histogram Equalization (CLAHE) method before edge detection. It aims to assess the extent to which local enhancement of contrast can help in extracting facial contours more effectively.

The data tested with the original data stage used Edge Detection and the use of CLAHE-enhanced and Edge Detection, as well as metric comparison and visualization. The results obtained showed that the value of the number of contours using CLAHE reached ±3,000 and with CLAHE on average ±10,000 – 20,000. The visualization results of the use of CLAHE and without CLAHE are presented in Fig 4.

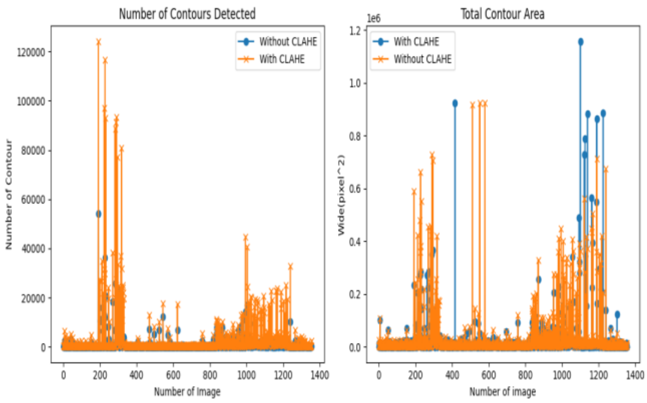

Fig 4. Comparison CLAHE

The results of the tests carried out can be concluded that with CLAHE the number of contours is much more numerous and fluctuating (up to 120,000 contours in some images) This suggests that CLAHE increases edge detection sensitivity, perhaps even too aggressive in some cases (over-detection). Whereas without CLAHE the contours are more stable and low, usually <10,000, this suggests that without increased contrast, many edges are not detected (especially in dark images). CLAHE manages to clarify the structure of the image, resulting in more detected edges. However, the number of contours that are not necessarily of good quality need to be analyzed along with the total contour area. For the contour area with CLAHE the contour area is quite large, but more stable and consistent. Many small contours account for a moderate total area. Without CLAHE some images show a huge spike in contour area (>1 million pixel²). This happens even if the number of contours is small that is, one or two large contours are detected. There are sharp spike anomalies in certain images possible due to high noise or dominant areas without segmentation. The interpretation without CLAHE detection can be too crude, failing to recognize small details, but instead detecting one large block. Using CLAHE detects more detail and spreads even if each contour is not too large. The results of the analysis summarize the overall

Table I. Result and Resume

Aspect	With CLAHE	Without CLAHE
Facial edge clarity	Less clear, many faces are dim	Sharper, more visible edges
Number of edges detected	A little, tend to be conservative	A lot, including small noise
Contour stability	Stable yet low	Fluctuating, depending on intensity
False Edges	Lower	Higher

IV. CONCLUSION

The conclusions of this study are:

a. CLAHE significantly increases the number of contours detected from edge detection results. The average number of contours increases dramatically, with some images even reaching more than 100,000 contours. This shows that CLAHE is able to improve local contrast and bring out more edge details.

b. Total area of contours with CLAHE is more stable, although the number is high. Without CLAHE, some images show a very large spike in contour area as only a large portion of the dominant edge is detected.

c. CLAHE usage recommendations are suitable for high-contrast imagery and suitable for dim or dark images.

Suggestions for further research are as follows:

If possible, further evaluate with ground-truth bounding boxes to calculate objective metrics such as IoU, precision, and recall.

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