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Fuzzy Contrast Enhancement Techniques Using Rule-Based System and Intensification Operator

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ABSTRACT

Contrast enhancement is a crucial step in digital image processing to ensure the production of high-quality images. Image contrast needs to be sufficient to ensure clear image visualization so that the image can be used well in various fields. Typically, images suffer from uneven lighting and low contrast. These two problems have different causes which are non-uniform illumination due to the light source being behind the object while low contrast is due to poor dynamic range. This paper presents two distinct fuzzy techniques designed to address the nuanced concept of contrast that utilize rule-based system and intensification operator, respectively, to handle the inherent vagueness associated with the concept of contrast. The fuzzy rule-based system calculates the intensity value of the output image based on the contrast measure (standard deviation) of the input image, thereby enabling effective contrast enhancement for low contrast images. Meanwhile, the fuzzy intensification operator aims to accentuate the differences in intensity levels within the image, thereby enhancing the contrast between various features and details. The experimental results show better image contrast is obtained using both methods. However, fuzzy rule-based approach shows more images with better quality compared to the intensification operator approach. The performance of these techniques is evaluated both visually and quantitatively.

1. Introduction

In digital image processing, contrast enhancement is crucial to producing high-quality images with enhanced clarity. High-quality images are useful in many different fields and provide improved visual effects. For example, improving the quality of fingerprint images makes it possible to classify them and use them for related applications such as suspect identification at crime scenes, access verification, customs verification, and so on [1]. The profession of medicine likewise places a high priority on image enhancement. Medical images produced by imaging devices or signal processing algorithms, such as ultrasound images, magnetic resonance imaging (MRI) images, computed tomography (CT) images, and positron emission tomography (PET) images, are frequently subject to noise. Images with noise may be less clear and more challenging to diagnose and assess diseases.

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Therefore, for later phases of medical image processing, minimizing noise in medical images is crucial [2].

Low contrast in images is frequently the result of insufficient lighting during the image collecting process. Therefore, specialized methods are needed to deal with this problem. There are various of methods that have been introduced by scholars, that range from classical, fuzzy, and advanced fuzzy approaches. One example of the classical methods is the histogram equalization (HE). This method modifies the image's contrast for enhancing image quality [3]. Sharma and Kumar [4] suggested improving the contrast of chest X-ray images by combining HE and CLAHE techniques. At the same time, noise reduction such as median filter and discrete cosine transform are also used to reduce the noise produced by CLAHE in order to produce high-contrast color images. The final output which is colour images can help in the identification of X-ray intrinsic details.

Alsaygh and Al-Ameen [5] used Noncomplex Multiphase Algorithm to increase the contrast of scanning electron microscopy images. The regularization procedure is carried out by using every pixel of the input image and the output of the regularization procedure will be used to add $\tau = 0.1$ to get the additional result ($T_{(i,j)}$) so that log of zero which is infinity can be avoided. After that, $T_{(i,j)}$ will be used in the gamma-corrected cumulative distribution function of the log-uniform distribution (GCCDFLUD) method. The GCCDFLUD output is then used in the automated histogram expansion (AHE) method to produce the final output which is the image after increase the contrast. The final image results are more attractive in visual and do not has unwanted effects. Besides, the image processing time also has excellent performance.

In 2023, Yang *et al*., [6] proposed an adjustable INT operator that has greater flexibility in enhancing images. This operator includes a parameter '*k*' that is related to the image pixel's local gradient, providing adaptability to different image contexts. In 2022, Yang *et al*., [7] introduced fuzzy method by using an improved fuzzy c-means clustering. In the same year, Yang *et al*., [8] applied a new intensifier operator to enhance fuzzy images. An application on contrast improvement by using advanced fuzzy technique on Flat EEG images was presented by Zenian *et al*., [9]. In addition, Yogish *et al.,* [10] focuses on improving the quality and clarity of microscopic medical images through the use of fuzzy logic. By applying fuzzy logic techniques, the paper aims to enhance the visual details and improve the accuracy of analyzing microscopic medical images**.** Trung [11] discusses a novel method for improving the contrast of medical images using fuzzy clustering and enhancement operators.

In this paper, two distinct fuzzy techniques are presented to address the nuanced concept of contrast. The first technique utilizes a fuzzy rule-based system that leverages the inherent vagueness of contrast with a well-defined set of rules. This approach enhances contrast in low-contrast images by calculating the intensity of the output image from the contrast measure (such as standard deviation) in the input image. The second technique uses a fuzzy intensification operator. By highlighting the contrast between various features and intricate details within the image, this operator emphasizes the differences in intensity levels across the image. Both a visual and a quantitative assessment is conducted in order to assess the performance of these techniques.

Measures such as contrast enhancement metrics provide a standard way of comparing the effectiveness of different techniques. Qualitative visual evaluations also provide insights into the enhanced images' perceptual quality. Both techniques produce improved contrast in images. However, the fuzzy rule-based approach showcases a higher frequency of images with superior quality compared to the intensification operator approach. These findings emphasize the effectiveness of the fuzzy rule-based system in addressing the challenges of contrast enhancement. In conclusion, the presented techniques provide valuable contributions to the field of image processing by effectively addressing contrast enhancement. Their distinctive approaches offer a range of benefits and trade-offs, underscoring the significance of selecting the most suitable technique based on the specific requirements of the task at hand.

2. Methodology

Fuzzy image enhancement is a technique that leverages fuzzy logic to enhance the quality of images. Fuzzy theory is particularly suitable for image processing tasks due to its ability to handle linguistic expressions in problem solutions. The process of fuzzy image enhancement involves several distinct steps. Initially, the intensity values of the image's gray levels are mapped onto the fuzzy plane using a membership function. Subsequently, the membership function is adjusted to refine the mapping process. Finally, the fuzzy plane is remapped back to the intensity values of the image's gray levels. Fuzzy image enhancement encompasses a range of techniques, including fuzzy contrast adjustment, subjective image enhancement, fuzzy image segmentation, and fuzzy edge detection [12,13]. There are two methods that will be used in this work to improve image contrast, namely FRBS and FIO. The process for both methods will be explained in detail in this section.

2.1 Fuzzy Rule-Based System

The Fuzzy Rule-Based System (FRBS), also known as Fuzzy Inference System (FIS), encompasses the utilization of membership functions, fuzzy logic operators, and If-Then rules. It serves as a non-linear mapping technique that employs fuzzy reasoning and If-Then rules to generate outputs. This system finds applications in various domains, including automatic control, data classification, decision analysis, and expert systems. Among the models based on fuzzy rules, the Takagi-Sugeno (TS) Model is noteworthy. The TS model features a fuzzy input and a crisp output. While similar to other fuzzy rule-based models like the Mamdani Model in most aspects, the TS Model differs in the conclusion part. In the Mamdani Model, the conclusion part comprises a fuzzy set, whereas in the TS Model, it involves a linear function [14,15]. The fuzzy rule formulation for the TS Model is as follows:

$$IF\ x\ is\ A\ AND\ y\ is\ B\ THEN\ z\ is\ f(x,y)$$

where x, y and z are linguistic variables, A and B are fuzzy sets on the universal discourse X and Y and $f(x,y)$ is a mathematical function.

Contrast enhancement using Fuzzy Rule-Based System involves employing the Takagi-Sugeno (TS) Model as its foundation. The traditional TS Model encompasses three essential steps: fuzzification, membership modification through if-then rules, and defuzzification. However, a study by Ahmadkhani and Moghaddam [16] identified a weakness in this approach. The weakness lies in the fact that the singleton value used in the defuzzification process is typically determined by the designer and not based on the input image itself. Consequently, the contrast improvement achieved using this approach may only be suitable for specific images. To address this limitation, the FRBS method adjusts the singleton value utilized in defuzzification based on the standard deviation of the input image. This adaptive approach ensures that the contrast enhancement is more tailored to the specific characteristics of the image. The steps involved in the FRBS method are outlined as follows [17,18]:

a) Change the image input to the form of double precision values.

b) Fuzzification

Fuzzification is applied to each pixel within the input image, converting its numerical value into the corresponding fuzzy domain. For input pixels, five distinct fuzzy sets are defined: black, dark gray, gray, light gray, and white. Two types of membership functions, namely Triangular and Trapezoidal, are employed in this process. Triangular membership functions are utilized for the dark gray, gray, and light gray fuzzy sets, while Trapezoidal membership functions are used for the black and white fuzzy sets. The singleton values for the darker gray and lighter gray fuzzy sets are determined using the Fuzzy Rule-Based System (FRBS) based on the standard deviation of the input image.

c) Calculate standard deviation of input image

In this step, the standard deviation of the input image is computed and utilized in the subsequent determination of the singleton values. The standard deviation serves as a measure of variability or dispersion within a set of values. A lower standard deviation suggests that the values are closely clustered around the mean, while a higher standard deviation indicates greater dispersion from the mean. The root mean square (RMS) contrast method can be employed to calculate the standard deviation of the image as in Eq. (1).

$$\sqrt{\frac{1}{MN}\sum_{i=0}^{N-1}\sum_{j=0}^{M-1}\left(I_{i,j}-\bar{I}\right)^2} \quad (1)$$

where $I_{i,j}$ is the pixel value of the size image $M \times N$ and $\bar{I}$ is the mean of image pixels.

d) Determination of singleton value using FRBS

In order to determine the singleton values for the darker gray and lighter gray fuzzy sets, the Fuzzy Rule-Based System (FRBS) is employed. This involves mapping the standard deviation of the input image to a value ranging between 0 and 0.25. For input standard deviations, three fuzzy sets are defined: low standard deviation, medium standard deviation, and high standard deviation. The low and high standard deviations are characterized by Trapezoidal membership functions, while the medium standard deviation employs Gaussian membership functions to represent the standard deviations in the fuzzy domain. The ranges of these three fuzzy sets were determined through observations of the standard deviations exhibited in low-contrast and high-contrast images. The singleton value of the output fuzzy set is as follows:

i) mf1 = 0
ii) mf2 = 0.125
iii) mf3 = 0.25

Then, the if-then rule is defined as follows:

i) IF Low Standard Deviation THEN mf1
ii) IF Medium Standard Deviation THEN mf2
iii) IF High Standard Deviation THEN mf3

e) Determination of pixel output using FRBS based on the singleton value calculated

This step determines the rules used in FRBS to enhance image contrast. The if-then rule for each image pixel is as follows:

i) IF Black THEN Black
ii) IF Dark Gray THEN Darker Gray

iii) IF Gray THEN Gray
iv) IF Light Gray THEN Lighter Gray
v) IF White THEN White
vi) IF Dark Gray THEN Black
vii) IF Light Gray THEN White

f) Defuzzification

During the defuzzification process, a weighted average approach is employed as in Eq. (2). The resulting crisp value obtained from this process represents the pixel value of the image after undergoing contrast enhancement.

$$Output = \frac{\sum_{i=1}^{B} w_i z_i}{\sum_{i=1}^{B} w_i} \tag{2}$$

where w_i is the weights applied to x values and z_i are data values to be averaged.

2.2 Fuzzy Intensification Operator

Fuzzy Intensification Operator (FIO) is a technique that can effectively enhance image contrast by reducing ambiguity. The general algorithm for FIO can be summarized as follows:

a) Fuzzification of gray level, represented as $\mu(g)$
b) Modification of membership using the intensification operator, denoted as $\mu'(g)$. This operator is defined as

   $2[\mu(g)]^2$ if $0 \le \mu(g) \le 0.5$ and as $1 - 2[1 - \mu(g)]^2$ if $0.5 < \mu(g) \le 1$

c) Defuzzification process to obtain the new gray level, g'_{mn}.

By employing this algorithm, FIO effectively adjusts the membership values of gray levels, leading to improved contrast in the resulting image. Each of the pixel value is used in the FIO method by carried out the following step:

i) Fuzzification by using Eq. (3)

$$\mu(g) = \left[1 + \frac{g_{max} - g_{mn}}{F_d}\right]^{-F_e} \tag{3}$$

where $\mu(g)$ is the degree of brightness, g_{max} is the maximum gray level, g_{mn} is the intensity value of pixels (m, n) in the input image, F_e is the exponential fuzzifiers and F_d is the denomination fuzzifiers. Suitable values for F_e is 1 and 2. F_d can be calculated by using Eq. (4)

$$F_d = \frac{g_{max} - g_{mid}}{0.5^{-\frac{1}{Fe}} - 1} \tag{4}$$

where g_{mid} is the medium gray level.

ii) Membership Modification by using Eq. (5)

$$\mu'(g) = \begin{cases} 2[\mu(g)]^2 & if\ 0 \le \mu(g) \le 0.5 \\ 1 - 2[1 - \mu(g)]^2 & if\ 0.5 < \mu(g) \le 1 \end{cases} \tag{5}$$

iii) Defuzzification by using Eq. (6)

$$g'_{mn} = g_{max} - F_d\left(\left(\mu'(g)\right)^{-\frac{1}{F_e}} - 1\right), \tag{6}$$

$$\left(1 + \frac{g_{max}}{F_d}\right)^{-F_e} \leq \mu'(g) \leq 1$$

2.3 Image Quality Measurement

Image quality measurement can be used to measure the improvement of image quality by using numerical values. Two measurements will be used in this study, namely the Mean Square Error (MSE) and Peak Signal to Noise Ratio (PSNR) [19].

2.3.1 Mean square error

Mean Square Error (MSE) is the most commonly used image quality measurement. MSE is the squared difference between the pixels of the original image and the pixels of the enhanced image. The equation for MSE is given in Eq. (7):

$$MSE = \frac{1}{MN}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\left(I_{i,j} - K_{i,j}\right)^2 \tag{7}$$

where $I_{i,j}$ pixel value of the original image with size $M \times N$ and $K_{i,j}$ is pixel value of the image after enhancement with $M \times N$. An MSE value close to zero indicates that the enhanced image quality is better.

2.3.2 Peak signal to noise ratio

Peak Signal to Noise Ratio (PSNR) is a measurement of image quality. PSNR is the ratio between the maximum possible signal power and the power of distorting noise. The ratio between the two images is in decibels. The PSNR is given in Eq. (8):

$$PSNR = 10\log_{10}\left(\frac{MAX_I^2}{MSE}\right) \tag{8}$$

where MAX_I is maximum possible pixels in the original image I. If the image pixel is an 8-bit unsigned integer (uint8), MAX_I is 255. If the image pixel is in a double precision value, MAX_I is 1. A high PSNR value indicates that the quality of the enhanced image is better. Usually, a PSNR value of more than 40 dB is considered very good [20].

3. Results

This section presents the experimental results and analysis of image contrast enhancement utilizing the Fuzzy Rule-Based System (FRBS) and Fuzzy Intensification Operator (FIO). The findings will be thoroughly examined and discussed. Table 1 shows the output images after enhanced by FRBS and FIO. From Table 1, the original gray image has low contrast but the image structure can still be observed while the image after contrast enhancement using FRBS and FIO has clearer structure compared to the original image. Table 2 represents the performance comparisons for both methods through the mean square error (MSE) and peak-signal-to-noise ratio (PSNR).

The PSNR and MSE are two popular metrics used to measure the quality of images, especially in the field of image processing. MSE is a type of error metric used to measure the average square difference between the original and a compressed or reconstructed image. By computing the square difference for every pair of corresponding pixels in the original and the experimental image, and then taking the average, one can obtain the MSE. On the other hand, PSNR is a more perceptual measurement and is commonly applied in image compression algorithms. PSNR compares the maximum potential power of a signal (image) to the power of corrupting noise that affects the quality of its representation. It's often expressed in logarithmic decibel scale. A higher PSNR indicates a higher quality image, or closer to the original. Both have their benefits and limitations. MSE can be influenced by the number of pixels in an image, which can make comparing image quality across different sized images a challenge.

Table 1
Output images using FRBS and FIO

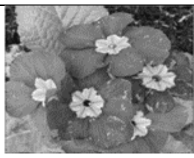
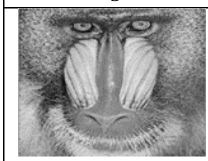
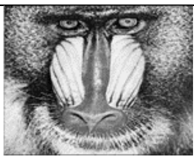
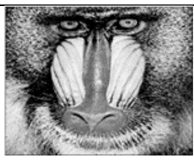
Original Image	Enhanced Image		Original Image	Enhanced Image	
	FRBS	*FIO*		*FRBS*	*FIO*
 Image 1			 Image 2		
 Image 3			 Image 4		
 Image 5			 Image 6		
 Image 7			 Image 8		
 Image 9			 Image 10		
 Image 11			 Image 12		

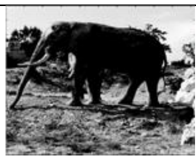
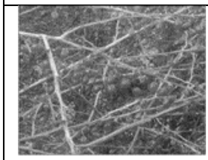
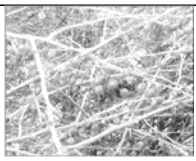
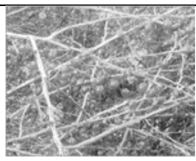
 Image 13			 Image 14		
 Image 15					

Figure 1 – Figure 2 show the graphs of comparisons. Based on Table 2 and Figure 1, the images after contrast enhancement using FRBS and FIO obtain good MSE results, which are close to zero. Overall, the contrast-enhanced images using FRBS are of better quality compared to FIO except for Image 8, Image 11, Image 14, and Image 15. For FRBS, the quality of Image 6 after contrast enhancement is the best while the quality of Image 11 after contrast enhancement is not as good as the other images. For FIO, the quality of Image 15 after contrast enhancement is the best while the quality of Image 10 after contrast enhancement is not as good as the other images.

Most of the images after contrast enhancement using FRBS and FIO obtain good PSNR results which have high PSNR values. Overall, the contrast-enhanced images using FRBS have better quality compared to FIO except for Image 8, Image 11, Image 14, and Image 15. For FRBS, the quality of Image 6 after contrast enhancement is the best while the quality of Image 11 after contrast enhancement is not as good as the other images. For FIO, the quality of Image 15 after contrast enhancement is the best while the quality of Image 10 after contrast enhancement is not as good as the other images.

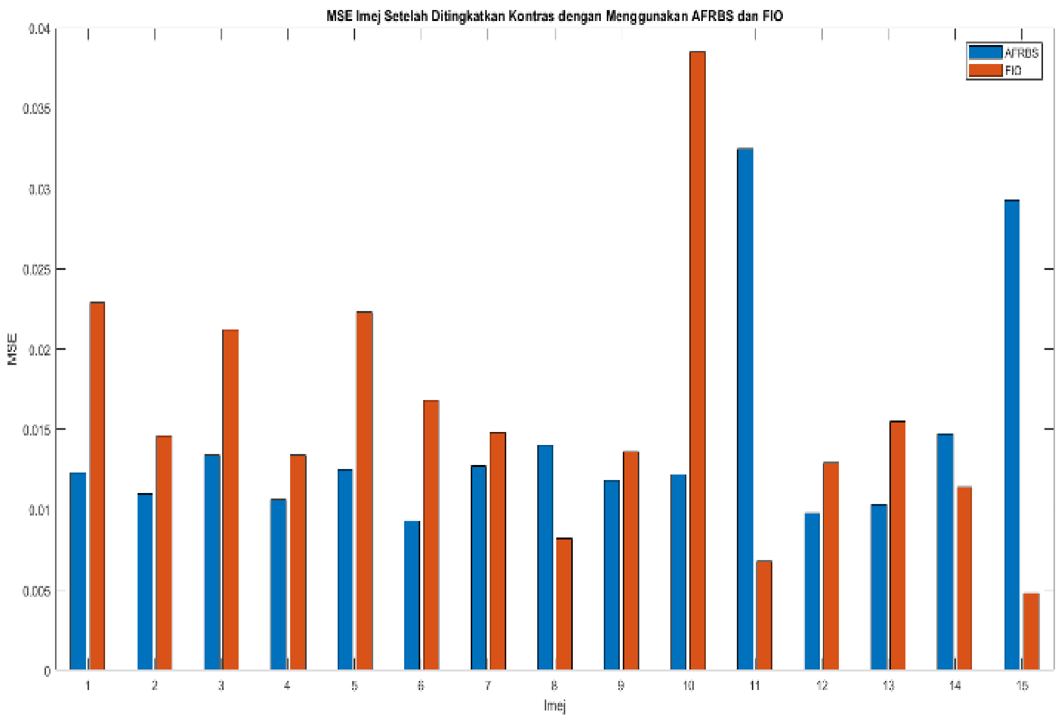


Fig. 1. Mean square error comparison

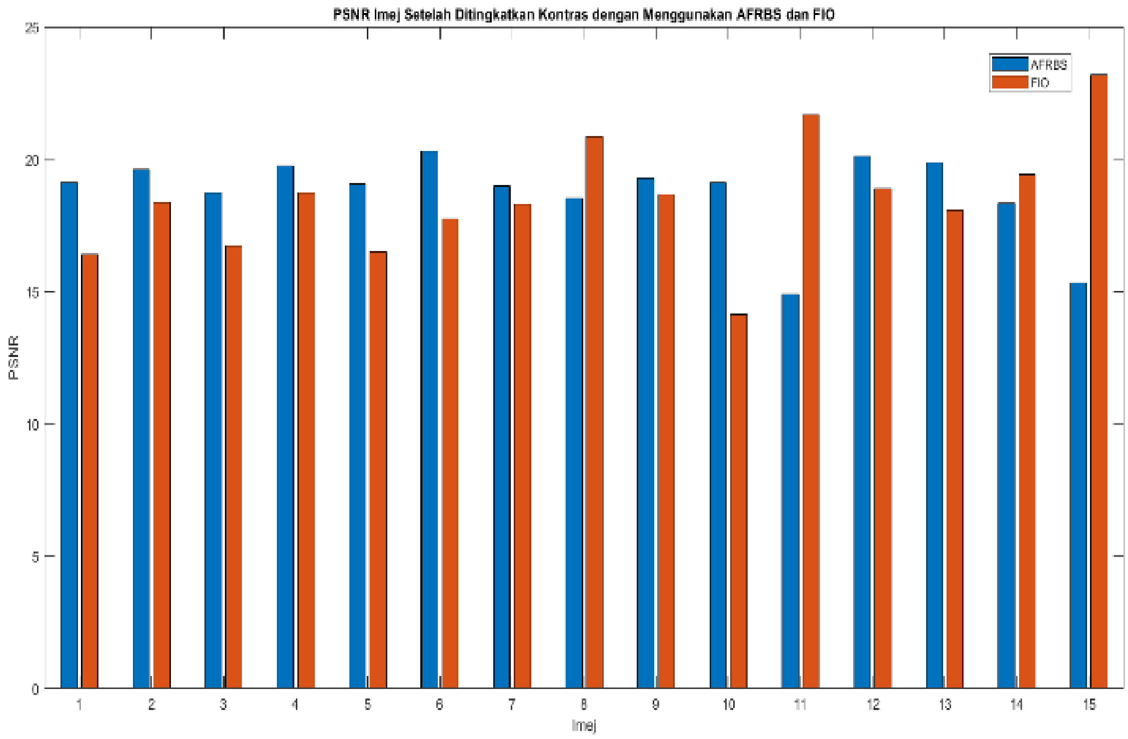


Fig. 2. Peak signal to noise ratio comparison

Table 2
Performance comparisons

Image	MSE		PSNR	
	AFRBS	FIO	AFRBS	FIO
Image 1	0.0123	0.0229	19.1033	16.4052
Image 2	0.0110	0.0146	19.5963	18.3591
Image 3	0.0134	0.0212	18.7187	16.7266
Image 4	0.0106	0.0134	19.7436	18.7145
Image 5	0.0125	0.0223	19.0403	16.5086
Image 6	0.0093	0.0168	20.3025	17.7458
Image 7	0.0127	0.0148	18.9730	18.2890
Image 8	0.0140	0.0082	18.5291	20.8489
Image 9	0.0118	0.0136	19.2703	18.6503
Image 10	0.0122	0.0385	19.1230	14.1500
Image 11	0.0325	0.0068	14.8859	21.6728
Image 12	0.0098	0.0129	20.1042	18.8928
Image 13	0.0103	0.0155	19.8640	18.0849
Image 14	0.0147	0.0114	18.3368	19.4238
Image 15	0.0293	0.0048	15.3286	23.1799

4. Conclusions

This study shows the potential of using two different fuzzy techniques in improving image quality. Both methods are compared and able to produce good image quality. However, the FRBS shows better results for most images except for Image 8, Image 11, Image 14 and Image 15. Level of enhancement in images can be measured by using PSNR and MSE. Higher PSNR values and lower MSE values show better output images. The methods employed in this work are based on the ordinary fuzzy approach. However, there are certain limitations associated with the use of these methods. They may not adapt well to changes in the imaging environment or variations in lighting conditions. Additionally, the rule-based systems rely on manually defined fuzzy rules and membership functions. As for future work, we propose the implementation of this method in medical imaging and other potential applications. Furthermore, the consideration of advanced fuzzy approaches could be helpful in overcoming the limitations of the ordinary fuzzy approach. It is worth noting that the choice of the right image enhancement techniques is crucial to address these limitations.

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