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Noise Reduction in CT Scan Images Using Wavelet Transform and Fuzzy Logic

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ABSTRACT

Images are often contaminated with noise due to sensor errors or during transmission. Noise in an image reduces the effectiveness of subsequent image processing operations, such as edge detection, segmentation, and object recognition. The use of an appropriate filter to reduce or eliminate noise in medical images shortens imaging time and consequently minimizes the exposure of patients to X-ray radiation. In the medical field, this improvement can enhance a physician's analysis of captured images, thereby reducing medical errors. In conventional noise removal methods using wavelet coefficient thresholding, the threshold value is uniformly applied to all image coefficients, leading to abrupt changes in values close to the threshold and causing image distortions. To address this issue, fuzzy logic is employed to achieve more effective noise reduction, overcoming the shortcomings of traditional thresholding methods and ensuring that the resulting image is not only quantitatively enhanced but also subjectively satisfactory. Due to its ability to model uncertain and approximate values, fuzzy logic can be effectively utilized for image denoising. By accepting approximation in data processing, fuzzy logic often provides more suitable behavior in many cases. This study aims to introduce an innovative approach for noise removal from CT scan images with the highest precision and sensitivity, considering evaluation criteria such as Peak Signal-to-Noise Ratio (PSNR) and Signal-to-Noise Ratio (SNR), among others. The proposed method integrates wavelet transform and fuzzy logic to establish a novel approach to noise reduction, overcoming existing challenges in this domain through fuzzy logic rules.

1. INTRODUCTION

Protective considerations, as well as the possibility of patient movement, impose limitations on imaging duration, resulting in significant noise in medical images. Consequently, the use of filters for noise reduction is often unavoidable. Identifying and correcting these distortions, either during imaging or in post-processing, is essential for enhancing diagnostic accuracy and preventing misinterpretations in medical assessments.

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In the past decade, wavelet transform-based methods have gained attention as a powerful approach to image noise reduction. Due to its high capability in providing time-frequency localization and its flexibility in selecting basis functions, wavelet transform has emerged as a robust tool in signal and image processing. Given these properties, wavelet transform is widely used in applications such as image compression, segmentation, watermarking, and noise reduction.

1.1. CT Scan Structure and Imaging Method

CT scanning is beneficial for diagnosing brain tumors, strokes, sinusitis, aortic aneurysms, chest infections, and diseases affecting organs such as the liver, kidneys, and abdominal lymph nodes.

The fundamental principle of CT scanning is based on the attenuation of X-ray beams as they pass through specific anatomical regions. Changes in the intensity of X-ray spectra passing through the body are recorded by detectors. If these changes are directly projected onto a film, a two-dimensional anatomical image—similar to conventional radiography—would be obtained. However, such variations in radiation intensity alone are insufficient for generating cross-sectional images. To obtain a cross-sectional image of the body, hundreds of X-ray beams must be projected from different angles, and the collected data undergo a reconstruction process to generate a tomographic image [1].

1.2. Noise and Its Types in CT Scan Images

The dominant factor influencing noise in CT scan images is the fluctuation in the number of X-ray photons. This fluctuation is itself affected by object attenuation, tube current, and detector size [2]. Common types of noise in CT imaging include Gaussian, impulse, and Poisson noise.

1.3. Wavelet Transform

The mathematical foundation of wavelet analysis traces back to Joseph Fourier's work in the 19th century [3]. While Fourier laid the groundwork with frequency analysis theory, wavelet analysis is historically considered a more recent development [4]. The wavelet transform is essentially an extension of the Fourier transform, with its fundamental concept introduced by Haar in 1910.

In 1984, a French geophysics student named Morlet applied wavelet principles to seismic signal analysis. Later, in 1986, Mallat and Meyer introduced the concept of multiresolution analysis, providing a rigorous mathematical framework for wavelet theory, which remained in place until the introduction of orthogonal wavelets in 1988.

Wavelets are quasi-wave mathematical functions that serve as basis functions for other functions, such as signals. The wavelet transform is a powerful tool for noise reduction, edge detection, gamma-ray analysis, and other applications.

Similar to the Fourier transform, the wavelet transform differs in that instead of being applied to the entire signal at once, it is performed on specific time segments known as frames or windows. By utilizing scaling and translation operations, the wavelet transform gradually improves time-frequency resolution, thereby compensating for the limitations of the Fourier transform.

This transform analyzes signals at different frequencies with varying resolutions, avoiding the uniform treatment of all frequency components, as seen in short-time Fourier transform. In the wavelet transform, both frequency resolution and time resolution vary in the time-frequency domain, without violating Heisenberg's uncertainty principle [5].

1.4. Discrete Wavelet Transform (DWT)

Computing wavelet coefficients for a given signal across all possible scales generates an enormous amount of data, whereas a suitable subset of these scales is often sufficient. This necessity leads to the use of the Discrete Wavelet Transform (DWT).

In the continuous wavelet transform (CWT), the signal is analyzed using a set of basis functions obtained through simple translation and scaling operations. However, in the discrete wavelet transform, a time-scale representation of a digital signal is obtained using filtering techniques. The signal to be processed is passed through filters with different cutoff frequencies at multiple scales [5].

The principles of discrete wavelet transform originate from a method known as subband coding, which was first introduced in 1976. The core idea of this method is similar to the continuous wavelet transform, where a discrete signal is represented in a time-scale domain using digital filters.

1.5. Noise Reduction or Removal in Images Using Wavelet Transform

The process of noise reduction or removal using the wavelet transform can be summarized in three steps:

(a) Decomposition:

This step involves selecting the wavelet function and the decomposition level (N), followed by performing the wavelet transform using the chosen wavelet function and decomposition level.

(b) Thresholding of Detail Coefficients:

For each decomposition level from 1 to N, a threshold is selected and applied to the detail coefficients.

(c) Reconstruction:

Wavelet reconstruction is performed using the original approximation coefficients and the modified detail coefficients for each level from 1 to N.

1.6. Thresholding in Wavelet Transform

Thresholding in the wavelet domain is an effective method for noise removal, making the determination of an optimal threshold a key research topic in recent years.

When applying the discrete wavelet transform (DWT), thresholding is used to enhance signal quality and eliminate noise. As previously mentioned, the objective of noise reduction is to ensure that the reconstructed signal closely resembles the original signal while preserving its essential characteristics.

Leveraging fuzzy logic, given its ability to model imprecise and uncertain values, can be highly effective in image denoising. By accommodating approximation in data, fuzzy logic often provides more appropriate behavior in many cases. Fuzzy systems are knowledge- or rule-based systems. Fuzzy theory is used to express and describe uncertainty and imprecision in events, originating from multi-valued logic principles.

Fuzzy logic mimics human reasoning, following a rule-based approach that aligns with the way the human brain processes information. A fundamental rule in fuzzy logic is structured as:"If x And y Then z."

2. TRADITIONAL METHODOLOGY

In general, an image retrieval system operates in two stages. In the first stage, visual features of images are automatically extracted as a dataset, which is then used for image indexing. In the second stage, this dataset is searched for visual features that match a query image to find the most similar images.

Visual features refer to observable attributes, such as whether an image contains noise. An image retrieval system requires a subsystem to process the input image and extract its low-level features. The dataset comprises images from which retrieval is performed. The analysis and results derived from this study are discussed in Chapter 9.

The query subsystem selects the appropriate features from the input image, measuring similarity between the feature vector of the input image and those of images in the dataset. The system then identifies the closest matching images.

Given the structure and functionality of image retrieval systems in noise removal, it is evident that their performance is highly dependent on the quality of the extracted features. Consequently, utilizing common methods for feature enhancement can lead to significant improvements in retrieval accuracy.

The overall structure of the image retrieval system for noise reduction and removal is illustrated in Figure 1.

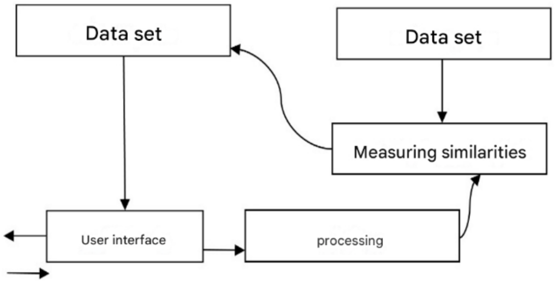


Fig. 1. Structure of the Image Retrieval System for Noise Reduction and Removal

3. PROPOSED METHOD

To summarize the approach implemented for reducing or removing noise in CT scan images, the process is as follows: First, the images are analyzed. If they contain noise, an appropriate wavelet transform either dB or Haar is applied, depending on the image type and noise characteristics. If the images are noise-free, a combination of Gaussian and salt-and-pepper noise is artificially introduced to them.

The key features considered in this study include:

Image variance,

Threshold level, which is determined based on edge detection, and

Noise type (Gaussian or salt-and-pepper), which is extracted using fuzzy logic rules.

Finally, the wavelet coefficients are generated based on the fuzzy system output.

The overall process of noise reduction or removal in CT scan images using wavelet transform and fuzzy logic is summarized in Figure 2. A detailed explanation of the methodology follows.

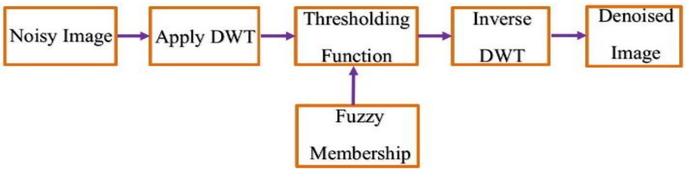


Fig. 2. Process of Noise Reduction or Removal in CT Scan Images

Initially, the input images must be normalized. During the preprocessing stage, input data—including both noisy and noise-free images—are normalized, and if necessary, enhanced to improve the system's detection performance. To achieve this, image resizing to a fixed dimension and median filtering are applied.

After preprocessing, the normalized input image is obtained. Each individual image in wavelet transform is represented by a two-dimensional pixel array, where the pixel values are integer numbers within the range [0, 255]. The wavelet transform initializes image processing in two stages:

- The noisy input image is considered as the initial image, to which denoising techniques will be applied.
- This process serves as a local search operation for enhancing the initial image.

The wavelet transform is selected due to its computational efficiency, providing faster processing compared to other techniques while yielding noteworthy results in the literature. At the end of the first stage, a decomposed representation of the image is obtained.

In the second stage, thresholding is applied to the detail coefficients. A randomly selected portion of the decomposed image is then sent for reconstruction, which consists of the following operations:

- Gaussian Blur: The image is filtered using a Gaussian filter, with a randomly selected filter size of either 3×3 or 5×5 pixels.
- Mean Filtering: The image undergoes mean filtering.
- Intensity Adjustment: The intensity of all pixels is scaled by a randomly selected factor within the range [0.7, 1.3].

Subsequently, the following steps are performed:

- Single-Pixel Row Selection: A row of randomly selected pixels is processed.
- Single-Pixel Column Selection: Similar to the previous method, but applied to columns instead of rows.
- Point-by-Point Random Selection: Pixels from the decomposition are randomly selected until a new image is formed.

After decomposition, if the random selection value within the range [0,1] is less than the local search rate of the algorithm, the new image may undergo local search operations. Once decomposition is complete, all pixels in the image are sorted individually based on their pixel values, and the optimal coefficient size is used as the fuzzy membership function for further processing. The Mamdani fuzzy model is adopted in this research.

Wavelets are signals that are localized in both time and scale and generally have an irregular shape. A wavelet is a wave-like function with finite duration and a zero mean. The term "wavelet" refers to the fact that the sum of wavelets equals zero. Wavelets exhibit oscillatory behavior along the horizontal axis, moving up and down. Additionally, many wavelets provide an ideal representation for compact image or signal representation, a property known as orthogonality, which prevents exaggerated data representation.

A signal can be decomposed into multiple translated or scaled representations of known features during feature extraction. The wavelet transform enables the decomposition of an image into its wavelet components, making it possible to segment the image. In this case, wavelet coefficients can be used to eliminate certain details selectively. Wavelets offer the unique advantage of isolating fine details in an image.

- Smaller wavelets can isolate extremely fine details,
- Larger wavelets can capture coarser details.

Moreover, various types of wavelets are available for selection, including Morlet, Haar, and others. A specific wavelet may provide a sparser representation compared to another, making it essential to experiment with different wavelet types to select the most suitable one.

In this study, discrete wavelet transform (DWT) is applied using Haar and Daubechies wavelets, with the choice of wavelet determined based on the input image.

A wavelet function has two key properties:

- The function exhibits oscillatory behavior, or a wave-like appearance.
- (Mathematical representation follows in Equation 1.)

$$\int_{-\infty}^{0} \Psi(t)|^2 dt < \infty \tag{1}$$

Which, in this case, means that most of the energy in $\Psi(t)$ is concentrated within a limited time interval, as expressed in Equation (2).

$$\int_{-\infty}^{0} \Psi(t) dt = 0 \tag{2}$$

The proposed method for noise removal is generally computed using Equation (3).

$$\text{Method}(I) = \left(\sum_{\Omega} \sqrt{1 + \beta^2 |\nabla I|^2}\right) + \frac{\lambda}{2}(I - I_0)^2 \quad (3)$$

Equation (3) is sensitive to the edges of the image and strives to preserve important features of the image. The term $(I - I_0)^2$ensures a certain degree of accuracy and reliability between the evaluated image III and the noisy image I_0. The parameter ∇I represents the adjustment of the total variation, while β and λ are balance parameters, and Ω refers to the total number of pixels in the image. By minimizing Equation (3), the objective is to reduce the total variation of the image while maintaining accuracy and reliability.

4. RESULTS

This study employs multiple evaluation metrics, including Mean Squared Error (MSE), Peak Signal-to-Noise Ratio (PSNR), Signal-to-Noise Ratio (SNR), and Precision, each of which is systematically analyzed. The results obtained from applying these evaluation methods are subsequently presented.

The implementation was conducted using MATLAB R2016b, utilizing a dataset composed of three standard images. The CT scan images analyzed in this study were retrieved from a medical image search engine linked to the U.S. National Library of Medicine [6]. Figures 3 through 5 illustrate the input images selected for the analysis.

Fig. 3. illustrate the input images selected for the analysis

Fig. 4. illustrate the input images selected for the analysis

Fig. 5. illustrate the input images selected for the analysis

Gaussian and salt-and-pepper noise are simultaneously applied to the input images from Figures 3 to 5, and the results are shown in Figures 6 to 8.

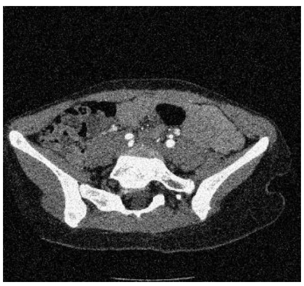


Fig. 6. Gaussian and salt-and-pepper noise are simultaneously applied to the input images from Figures 3

Fig. 7. Gaussian and salt-and-pepper noise are simultaneously applied to the input images from Figures 4

Fig. 8. Gaussian and salt-and-pepper noise are simultaneously applied to the input images from Figures 5

Now, using the proposed approach, which involves wavelet transform and fuzzy logic, the noise will be removed and reduced in the images. After applying the algorithm, the outputs will be shown in Figures 9 to 11.

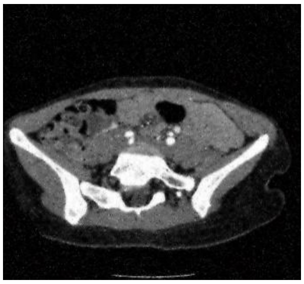


Fig. 9. Output image after noise reduction using wavelet transform and fuzzy logic

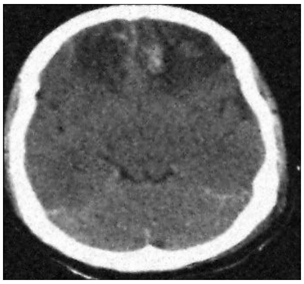


Fig. 10. Enhanced image following the application of the proposed denoising algorithm

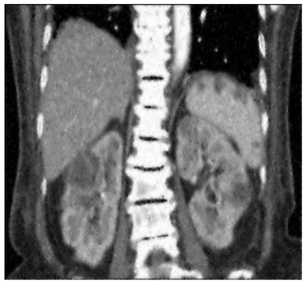
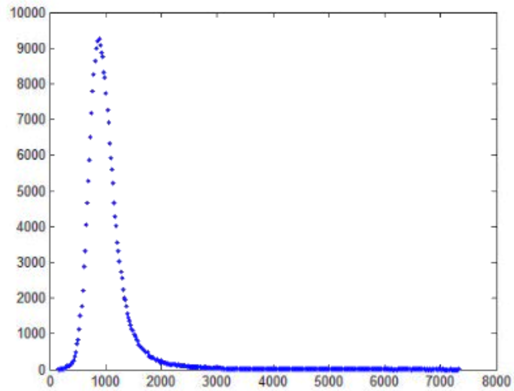
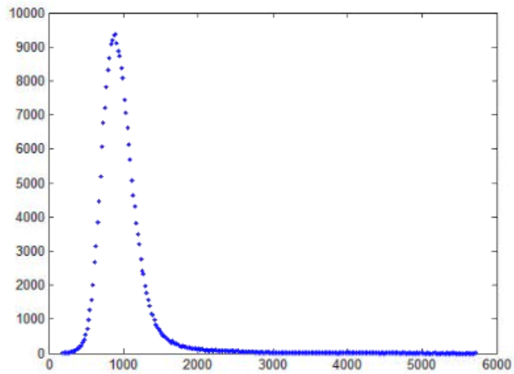


Fig. 11. Final processed image with improved clarity and reduced noise

Each image has a noise histogram, which for the output images 9 to 11 is shown in Figure 12.





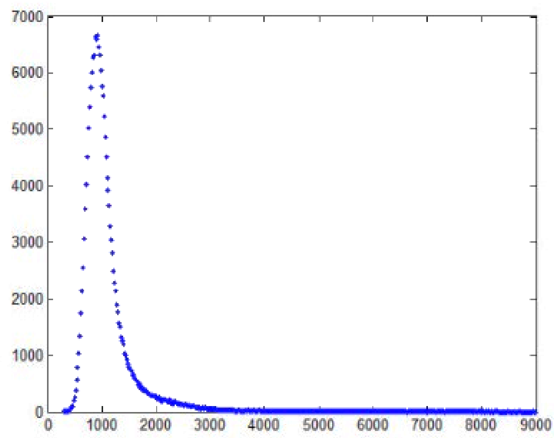


Fig. 12. Histogram after noise reduction for the three input images from Top to bottom, showing the results of noise removal execution.

As is evident from the images, improvements in noise reduction and, in some cases, complete noise removal have been achieved using the proposed method. Evaluation metrics for each image have also been considered, and the results for each image can be seen in Table 1. The average values are also provided.

Table 1. Evaluation results for the three images.

Images	**Accuracy (%)**	**SNR (dB)**	**PSNR (dB)**	MSE
First Input Image	99.4963	30.3223	117.8072	0.4975
Second Input Image	82.9269	38.2335	119.6289	0.4146
third Input Image	96.3074	31.7370	118.1330	0.4815
Average Result of the Three Images	92.9102	33.4309	118.5230	0.4645

Comparison of the results obtained with references [7] to [16] shows that the proposed method exhibits superior performance in terms of two metrics: peak signal-to-noise ratio (PSNR) and signal-to-noise ratio (SNR). However, in the metric of mean squared error (MSE), other methods demonstrate a relative advantage.

5. CONCLUSION

The development of image retrieval systems in noisy communication channels or similar environments dealing with noisy or distorted images requiring recovery is of significant importance. By creating such a system, the retrieval of corrupted images can be effectively accomplished. Image processing, as a suitable method in such tasks, is employed, and by combining machine learning techniques, it can handle various operations of these systems. In the medical field, CT scan images may become noisy due to patient movements and other factors, which complicate the disease diagnosis process for physicians. Therefore, providing methods that can effectively remove noise from CT scan images is vital and highly significant. The approach in this study utilizes a combination of wavelet transforms and fuzzy logic to reduce and remove noise from images. The wavelet transform combined with fuzzy logic processes the results and optimizes them in such a way that no essential parts of the image, such as edges, corners, and other important details, are removed, and it improves both the quantitative and qualitative aspects. The results indicate that the implemented approach has shown improvements in both the quantitative and qualitative aspects compared to previously reviewed methods, such as the mean squared error and peak signal-to-noise ratio metrics, with the final output image being more optimized in terms of noise reduction and quality enhancement.

Declaration

We acknowledge that we used ChatGPT to enhance the academic writing of our manuscript while ensuring the originality and integrity of our work.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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