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Development of ultrasonic imaging speckle reduction methods

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Abstract: *Speckle noise is a common issue in coherent imaging systems arising as an unwanted artifact during the image formation process. Addressing speckle reduction holds significant importance, particularly in ultrasound imaging. The presence of speckles in ultrasound images degrades image quality, posing challenges for human interpretation and diagnostic analysis. Numerous techniques have been proposed for mitigating speckle noise. This paper provides an overview of the updated speckle noise reduction models, along with various filters commonly employed for speckle reduction in ultrasound images. Given the prevalence of speckle noise in ultrasound imaging, it becomes crucial to denoise ultrasound images before extracting regions of interest. Accurate detection of regions is paramount, as the final segmentation results rely on it.*

Keywords: *Speckle, noise reduction, ultrasound, CNN, Wavelet, Despeckling*

1. INTRODUCTION

Ultrasound imaging is widely recognized as a non-invasive, safe, portable, cost-effective, and highly accurate medical imaging modality. It has become the diagnostic tool of choice in hospitals worldwide. However, the image quality of medical ultrasound is often limited due to various factors arising from both the physical phenomena involved in image acquisition and imperfections in the design of ultrasound systems [1]. While addressing the latter remains a challenge for engineers, effective signal-processing techniques are essential for compensating for undesirable physical effects. Consequently, significant efforts have been devoted to the development of signal processing tools aimed at combatting the primary impediment of ultrasound imaging—speckle noise.

Speckle noise is a characteristic artifact present in ultrasound images that arises from the interference of multiple coherent signals scattered by tissue structures. This phenomenon is inherent to coherent imaging modalities, where images are formed through the interference of echoes generated by transmitted waveforms interacting with variations or irregularities in tissue properties within the imaged region, also known as heterogeneities. These heterogeneities can include tissue composition, structure, density, or acoustic impedance differences [2]. The combination of acoustical echoes with varying phases and amplitudes gives rise to a complex interference pattern known as speckle noise, which can exhibit a range of intensities depending on the constructive or destructive nature of the interference. Unfortunately, speckle noise shows minimal correlation with the macroscopic properties of the biological tissues under examination, obscuring diagnostically significant details and hindering accurate interpretation. It manifests as a granular pattern that obscures fine details, reduces contrast, and impairs the accurate interpretation of ultrasound images. Consequently, mitigating speckle noise is of utmost importance in improving the diagnostic capabilities of ultrasound imaging.

However, it is well-known that speckle noise significantly impacts the quality and reliability of medical ultrasound by reducing image contrast and obscuring fine details. Speckle noise acts as a visual interference, causing blurring and smearing of important image features. This degradation hampers accurate interpretation and diminishes the diagnostic potential of ultrasound imaging. To address this challenge, researchers and engineers have developed image-processing methods specifically designed to suppress speckle noise. These methods, commonly referred to as despeckling methods, aim to enhance the quality of ultrasound images by reducing or mitigating the effects of speckle noise. By effectively suppressing speckle noise, these despeckling methods contribute to the restoration of image details, improvement of image contrast, and overall enhancement of image quality.

Despeckling methods employ various techniques and algorithms, ranging from traditional filtering approaches to more advanced model-based and machine learning-based methods. These methods analyze the statistical properties and

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spatial characteristics of speckle noise within ultrasound images, allowing for the development of effective noise reduction strategies [3]. By selectively smoothing or filtering the image while preserving important structural details and edges, despeckling methods can restore image clarity and enhance the visual interpretability of ultrasound scans.

The application of despeckling methods in medical ultrasound imaging has demonstrated their usefulness in clinical practice. Enhanced image quality through speckle noise reduction facilitates accurate visualization and identification of anatomical structures, lesions, and abnormalities. This, in turn, improves the reliability of diagnoses, assists in treatment planning, and enhances the overall effectiveness of ultrasound-based medical interventions.

2. Methodology

A comprehensive review of relevant literature, research papers, and government reports concerning the design and efficiency of RF power amplifiers (PAs) was conducted. This investigation utilized databases such as Google Scholar, Academia, and ResearchGate, incorporating sources like IEEE Xplore, Web of Science, and PubMed.

3. Literature review

Ultrasound imaging has significantly advanced over the years, and along with this progress, methods for reducing speckle noise a common artifact in ultrasound images have also evolved. Speckle noise, caused by interference patterns in coherent imaging systems, can obscure fine details and complicate image interpretation. As ultrasound technology has become increasingly integral to medical diagnostics, the development of effective speckle reduction methods has been pivotal. This paper summaries an overview of the evolution of the speckle reduction methods:

The initial attempts at speckle reduction involved basic filtering techniques, such as mean and median filters. Mean and median filters are fundamental techniques commonly employed for speckle reduction in ultrasound imaging. These filters aim to mitigate the unwanted granular patterns known as speckle noise, which can obscure important anatomical details and hinder accurate image interpretation.

The mean filter also referred to as the averaging filter operates by replacing each pixel's intensity value with the average intensity of the neighboring pixels within a specified window or kernel. The idea is to smooth out rapid intensity fluctuations caused by speckle noise while preserving the underlying structures. It is Simple and computationally efficient, Effective in reducing high-frequency noise components, and Smoothes noise without significantly affecting edges and fine details. However, it can lead to blurring of edges and fine structures and may not be effective for noise reduction if the noise levels are not uniform.

The median filter aims to reduce speckle noise while preserving edges and fine features. Instead of replacing a pixel's intensity value with the mean of neighboring pixels, the median filter replaces it with the median value within the kernel. It is less sensitive to outliers and extreme noise values and better at retaining details compared to the mean filter. However, it may not fully remove speckle noise in highly textured regions and can cause a minor loss of image detail due to the median operation.

Both mean and median filters are part of the family of linear filters, and their effectiveness depends on the characteristics of the speckle noise and the size of the filtering window. These filters are simple to implement and can serve as a baseline approach for speckle reduction in ultrasound images. However, it's important to note that while mean and median filters can reduce speckle noise, they may not be sufficient for more complex noise patterns or when fine details need to be preserved. In such cases, advanced techniques were introduced.

Figure 1 (a)Original image (b) After the median filter

Wavelet transform technique

The introduction of wavelet transforms marked a significant advancement. Wavelet-based methods decompose images into different scales, enabling selective denoising of high-frequency components. Wavelet transform-based speckle reduction techniques were introduced in the late 1980s and early 1990s. The concept of wavelet transforms had been around for some time before they were adapted for speckle noise reduction in various imaging applications, including ultrasound imaging [4]. The wavelet transform's ability to decompose an image into different scales and frequencies made it particularly suitable for speckle reduction. By analyzing and processing image details at various scales, wavelet-based methods could effectively suppress speckle noise while preserving important structural information. The 1990s saw the emergence of research papers and studies that explored the potential of wavelet transform in speckle reduction for ultrasound and other coherent imaging modalities [5]. As computational capabilities improved, these methods gained traction due to their ability to address the specific challenges posed by speckle noise. Over the years, wavelet-based techniques have been refined and adapted to different imaging scenarios. Today, they remain an important component of the toolkit for speckle noise reduction in various applications, offering a valuable approach to improving image quality and diagnostic accuracy.

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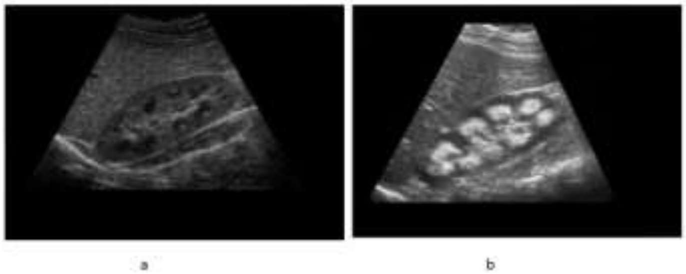

Figure 2 (a) Original Kidney image (b) Kidney after wavelet transform technique

Anisotropic diffusion technique

As understanding of speckle noise improved, researchers introduced anisotropic diffusion algorithms and adaptive filters in a paper that was published in 1990 by Perona and Malik in their paper titled "Scale-Space and Edge Detection Using Anisotropic Diffusion". Anisotropic diffusion is a technique that selectively diffuses image intensity values based on local gradient information. It aims to smooth out noise while preserving edges and fine structures. The rate of diffusion is adjusted according to the gradient magnitude, allowing more diffusion along flat areas and less diffusion near edges [6]. It effectively reduces speckle noise while preserving edges, it can also be Customizable to different image characteristics and Minimizes loss of fine structural details. However, Parameter tuning can be challenging and may still result in slight blurring near edges.

Adaptive filters adjust their filtering parameters based on the local characteristics of the image. These filters can be specifically tailored to the type of noise and features present in the ultrasound image. Adaptive weighted median filtering, for example, assigns different weights to neighboring pixels depending on their similarity to the central pixel. It can provide excellent speckle reduction tailored to specific image features. however, Parameter tuning might be required for optimal performance and it may still introduce minor blurring or artifacts in certain cases [7]. Both anisotropic diffusion and adaptive filters represent more sophisticated approaches compared to basic linear filters like mean and median filters. They take into consideration the local image content and adapt the filtering process accordingly, resulting in improved noise reduction while minimizing loss of image detail.

These methods have proven effective in addressing the challenges posed by speckle noise in ultrasound images, contributing to enhanced image quality and diagnostic accuracy. However, the choice between anisotropic diffusion and adaptive filters, as well as the specific parameter settings, often depends on the characteristics of the image and the desired trade-off between noise reduction and feature preservation.

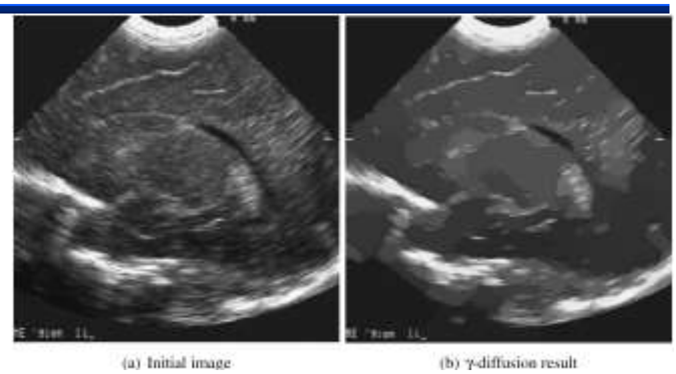

Figure 3: Images of before and after Anisotropic diffusion technique

Non-local Means (NLM) and Similar Techniques

Non-local Means (NLM) and similar techniques are advanced approaches widely utilized for speckle reduction in ultrasound imaging. These methods take advantage of similarities between image patches to effectively reduce speckle noise while preserving important structural information. NLM filtering is based on the principle that similar image regions should have similar intensity patterns. Instead of processing individual pixels, NLM considers small patches of pixels [8]. It calculates the weighted average of pixels within similar patches, with the weighting based on the similarity between patches. This way, NLM exploits redundant patterns in the image to effectively suppress speckle noise.

It is computationally intensive due to patch comparisons and requires careful parameter tuning for optimal results. Various techniques similar to NLM have emerged, building upon the concept of patch-based denoising. Some of these methods include Block-Matching 3D (BM3D), Guided Image Filter (GF), and Groupwise Non-local Means (GNLM). Similar technique's Computational complexity can be high, particularly for 3D methods and Parameter tuning may be required for best performance.NLM and similar techniques have demonstrated substantial success in reducing speckle noise in ultrasound images [9]. By exploiting the self-similarity present in the images, these methods efficiently denoise while retaining important anatomical details. The evolution of these techniques has led to variations and optimizations, expanding their applicability to various imaging scenarios and noise profiles. When choosing between NLM and similar techniques, as well as their variations, it's essential to consider factors such as the level of speckle noise, the desired amount of noise reduction, and computational constraints. These advanced methods contribute significantly to improving ultrasound image quality, leading to enhanced diagnostic accuracy and improved clinical utility.

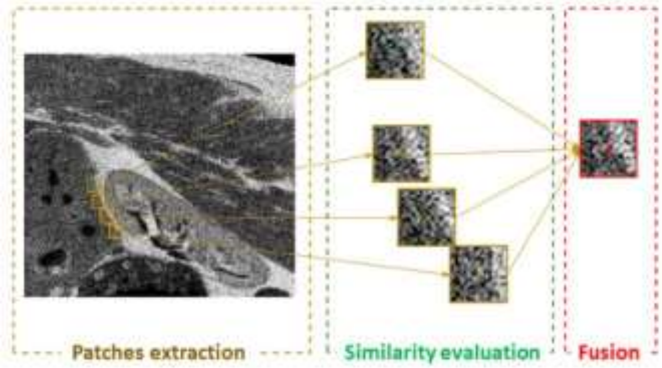

Figure 4: Block diagram of non-local means approach

Statistical and Model-based Approaches

Statistical methods, such as Lee and Kuan filters, utilized statistical properties of speckle noise for reduction. Model-based approaches, like the Gamma distribution model, provided insights into the underlying noise patterns.

Statistical and model-based approaches are sophisticated techniques commonly employed for speckle reduction in ultrasound imaging [3]. These methods leverage statistical properties of speckle noise and employ mathematical models to effectively suppress noise while preserving important image details. Here's how these approaches work in the context of ultrasound speckle reduction:

Statistical Approaches

The Lee filter is a statistical approach that suppresses speckle noise by estimating the local mean and variance of image patches. It replaces the central pixel's intensity with a weighted combination of the estimated mean and the original intensity. The weighting factors are based on the local variance and speckle noise characteristics [2]. Similar to the Lee filter, the Kuan filter estimates local statistics to determine the amount of noise present in a patch. It replaces the central pixel's intensity with a weighted combination of the estimated mean and a constant value related to the local standard deviation. Statistical approaches may not be as adaptive to image content as some other methods and Optimal parameter tuning can be important for performance

Model-based Approaches

The gamma distribution model is one of the model-based approaches that assumes that speckle noise follows a gamma distribution. By estimating the parameters of this distribution, a gamma filter can be designed to reduce speckle noise. This approach can be effective if the noise conforms to the gamma distribution assumption. More advanced model-based approaches employ stochastic models to represent the nature of speckle noise [10]. These models can capture complex statistical behaviors of speckles and provide a basis for designing effective denoising algorithms. These modes may require accurate knowledge of the noise distribution or model parameters and Can be more complex to implement compared to simpler techniques.

Both statistical and model-based approaches contribute to the toolbox of speckle reduction techniques. The choice between these approaches often depends on the availability of information about the statistical properties of the noise, as well as the desired level of adaptability and complexity. These methods play a crucial role in enhancing image quality for ultrasound imaging and contribute to improved diagnostic accuracy.

Advancements in Deep Learning

With the rise of deep learning, convolutional neural networks (CNNs) and other architectures revolutionized speckle reduction. These networks, trained on large datasets of noisy and clean images, learned intricate noise patterns and produced remarkable denoising results [3].

Convolutional Neural Networks (CNNs) have emerged as powerful tools for speckle reduction in ultrasound imaging. CNNs are a type of deep learning architecture that can automatically learn and extract relevant features from data, making them well-suited for denoising tasks.CNNs have shown remarkable success in speckle reduction for ultrasound imaging, producing denoised images with improved quality and diagnostic value [11]. Their ability to capture intricate noise patterns and preserve relevant anatomical details has made them an important tool in enhancing image quality and supporting accurate clinical diagnosis.

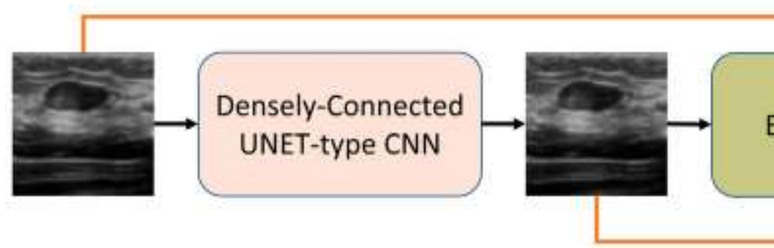

Figure 5: Block diagram of a convolution neural network used in speckle reduction

The evolution of speckle reduction methods in ultrasound imaging underscores the continuous effort to enhance image quality and diagnostic accuracy. As imaging technology and computational capabilities advance, researchers continue to refine and develop innovative techniques, contributing to the ongoing improvement of ultrasound-based medical diagnostics and patient care.

4. Conclusion

Speckle noise emerges in coherent imaging when the surface roughness of the imaged object aligns with the wavelength of the incident radiation. The presence of speckle noise within ultrasound images is undesirable, as it degrades image quality by affecting edges and intricate details, particularly in heterogeneous organs crucial for diagnostics. This type of noise is prevalent in various imaging and vision applications like ultrasound imaging and digital holography. To ensure accurate image data interpretation, reducing speckle noise becomes imperative. This paper delivers a concise introduction to speckle noise and offers a brief overview of popular filters discussed by various scholars. In future investigations, the paper will delve deeper into this subject and propose a frequency domain-based algorithm for speckle reduction, which promises reduced computation time. Through various techniques, it has been observed that the proposed method outperforms others, enhancing segmentation performance by accurately identifying boundaries and boosting processing speed. The findings of the literature survey underscore the necessity of speckle noise reduction as a pre-processing step for effective segmentation of ultrasound images, particularly those depicting deep organs like the liver and kidney. Subsequent explorations will encompass liver tumor segmentation, aiming to validate the proposed approach's accuracy through sensitivity and specificity measurements.

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