

Mathematical models for noise reduction in IoT image processing applications

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Abstract

IoT has opened the floodgates the importance use of image processing in areas like surveillance, auto-navigating vehicles, and smart healthcare. Nonetheless, noise in IoT-generated images largely distorts image quality as well as subsequent analytical operations that may be performed. The fundamental goal is to derive and test stable mathematical models that improve noise reduction while maintaining real-time computation that would be viable for limited IoT devices. The paper uses both first order Linear filtering techniques like Gaussian filters and Median and second order filters which are in the transform domain like Wavelet transforms. These techniques are then systematically invoked on images contaminated by Gaussian, Salt-and-Pepper and Speckle noise types for performance evaluation. Simulation studies using MATLAB with camera man image 'cameraman.tif' for standard prove the Wavelet transforms outperforms in noise reduction attaining up to 15.3 dB PSNR and 0.92 SSIM for better structural preservation. On the other hand, Gaussian

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and Median filters take 0.05 – 0.07 seconds to process and hence well suited for real-time applications.

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1. Introduction

IoT has transformed several industries through interconnected objects that gather comprehensive data and also transfer the same for analysis and image processing is vital area in areas like security systems, own driven automobiles and smart health care [1]. The IoT ecosystems require accurate object detection, monitoring and decision making which require the high quality image data [2]. However, noise is another factor obtained from IoT-generated images which becomes another problem as it hinders image quality and impacts the efficiency of the subsequential analysis to be performed [3]. The noise present in IoT image data may result from the sensor characteristics, interferences during transmission, as well as some environmental factors, and can produce different types of noise [4], for example, Gaussian, Salt-and-Pepper, and Speckle [5]. Consequent challenges of noise reduction in IoT image processing concerns are made worse by the IoT limitations of devices that are usually characterized by scarce processing power, memory, and energy [6]. These constraints therefore require the design and implementation of effective noise reduction processing that could also run in the constrained environments typical of the IoT systems [7]. This work seeks to propose and assess innovative mathematical algorithms specific to noise adversary in IoT image processing with emphasis on amplifying the efficiency of noise minimization [8].

2. Literature Survey

Noise in image processing comes in various forms and fields some of which are Gaussian noise (GN), Salt-and-Pepper noise (SPN), Speckle noise (SN) which arises due to imperfections of the spreading media or a result of inability of sensor to capture perfect image, noise that arises during the transmission process and environmental noise [9]. These noise types reduce the quality of images and challenge tasks of object detection, recognition and computation that is greatly attached to IoT devices. Noise reduction techniques from conventional methods mean filters are one of the extensively studied with Gaussian and Wiener filters forming the basic approaches by simply blur images and removing random noise [10]. There are other kernels which can be useful in noise reduction without erasing the edges and the other crucial image features these are Non-linear filters as Median and Bilateral filters [11]. However, these methods are still not easy to be used in IoT Image processing scenarios given the following reasons [12]. Thus, IoT environments are based on resource limited devices with limited processing capability [13], memory and energy and makes

high computation demanding existing noise removal strategies infeasible [14]. Additionally, various present day techniques do not provide sufficient noise filtering [15] while not compromising the real time computing capacity which are unquestionably necessary in applications like surveillance and self-propelled systems [16]. In this literature, there is a clear research gap in the creation of noise reduction models that are suitable for the resource-limitation condition of IoT [17,18], indicating the need for additional studies that develop novel noise reduction criteria that did not compromise the noise reduction proficiency of the model but are also run within the resource-limited environment.

3. Proposed Method

The proposed noise removal approach for IoT image processing applications presented in this paper is intended to provide maximum quality improvements within IoT context that are replete with restrictions on available computational resources. Figure 1, presents the proposed system, starting with Image Acquisition through IoT gadgets including sensors and cameras.

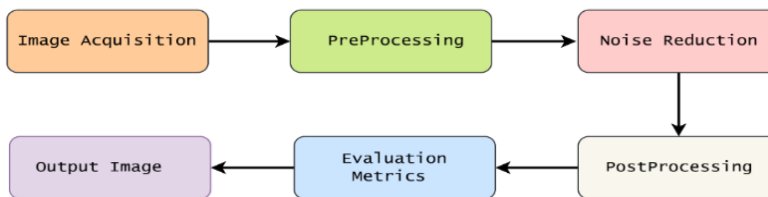


Figure 1

Proposed System Diagram for Noise Reduction in IoT Image Processing

The raw image data obtained from the two stages are vital for subsequent Image Processing tasks. Pre-processing is the first stage where the images are basically enhanced by resizing and normalization in order to enhance the characterization of noise. The process begins with Noise Type, Noise Identification function decides whether the noise that exists is Gaussian, Salt-and-Pepper, or Speckle as shown in Figure.2. Based on this classification, the system selects the most appropriate filtering technique: Namely, Gaussian filtered for GN, Median filtered for SPN, Wavelet Transforms for SN. Such an approach guarantees that each noise type is treated with the kind of filtering approach that removes most of the noise without distorting essential image features. After that, the Post-processing phase may include post adjustments that aim to make the denoised images even more sharpened and contrasted in order to provide them better for further IoT applications including surveillance and IoT autonomous navigation. The Evaluation Metrics component quantifies and measures the efficiency of the noise reduction process, the quality of which is evaluated by the PSNR and the Structural Similarity Index (SSIM), in order to ensure that its quality is optimal.

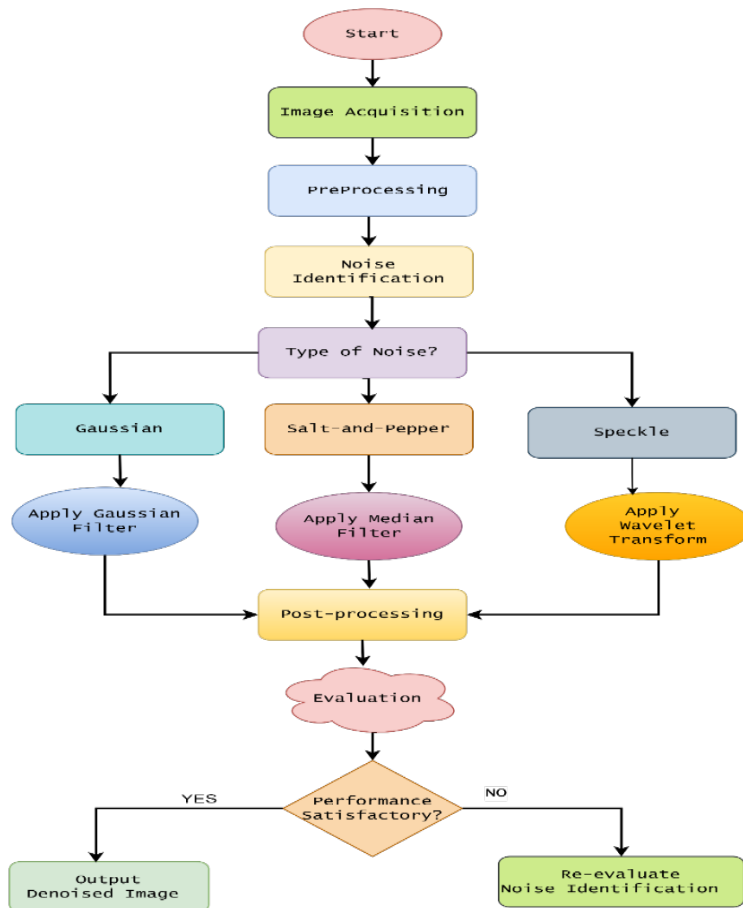


Figure 2

Flow Chart of the Noise Reduction Process in IoT Image Processing

4. Mathematical Model

Noise in image processing is mathematical modeled using various distributions and these are equally used to represent various types of noise. Gaussian noise is defined as: $N(x, y) \sim N(0, \sigma^2)$ where σ denotes the standard deviation. Salt-and-Pepper noise is modeled by randomly setting pixel values to the minimum or maximum intensity levels. Speckle noise is represented as multiplicative noise:

$$I'(x, y) = I(x, y) + I(x, y)N(x, y)$$

where $I(x, y)$ is the original image intensity.

Linear filtering techniques, such as the Gaussian filter, apply a convolution operation expressed by:

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

where the kernel size and standard deviation σ control the smoothing effect. The Wiener filter minimizes the mean square error and is formulated as:

$$W(u, v) = \frac{H^*(u, v)}{|H(u, v)|^2 + \frac{S_n(u, v)}{S_x(u, v)}}$$

incorporating the signal and noise power spectra.

Non-linear filtering models with a window function, and the Bilateral filter, which combines spatial and intensity domains:

$$BF(x) = \frac{1}{W_p} \sum_{x_i \in \Omega} G_{\sigma_s}(\|x_i - x\|) G_{\sigma_r}(|I(x_i) - I(x)|) I(x_i)$$

thereby preserving edges by considering both spatial closeness and intensity similarity. Transform domain approaches utilize the Fourier transform:

$$F(u, v) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x, y) e^{-j2\pi(\frac{ux}{M} + \frac{vy}{N})}$$

and Applied Discrete wavelet transforming for, multi resolution analysis followed by thresholding mechanism for rejecting noise. Filtering methods are used to reduce computational load by using sparse vectors and, at the same time, optimal algorithms are applied to control noise reduction effectiveness with limited computational resources which characterize IoT devices.

5. Algorithm

The noise reduction algorithm for IoT image handling presents a number of well-ordered steps which aim at providing maximum efficiency of noise reduction within the context of the Internet of Things while utilizing only a limited number of resources.

The pseudocode for the algorithm is outlined below:

```

BEGIN NoiseReductionAlgorithm
  INPUT: RawImage
  PREPROCESS:
    Resize(RawImage)
    Normalize(RawImage)
  IDENTIFY_NOISE:
    NoiseType = DetectNoise(RawImage)
  APPLY_FILTER:
    IF NoiseType == Gaussian THEN
      DenoisedImage = GaussianFilter(RawImage)
    ELSE IF NoiseType == SaltAndPepper THEN
      DenoisedImage = MedianFilter(RawImage)
    ELSE IF NoiseType == Speckle THEN
      DenoisedImage = WaveletTransform(RawImage)
  POSTPROCESS:
    Sharpen(DenoisedImage)
    AdjustContrast(DenoisedImage)

```

```
OUTPUT: DenoisedImage
END NoiseReductionAlgorithm
```

This algorithm guarantees optimal noise attenuation necessary for the appropriate functionality of IoT apparatus, making it possible to achieve effective image amplification in various IoT applications.

6. Results and Discussions

MATLAB simulations were carried out to assess the usefulness and performance of the recommended mathematical models of noise reduction for IoT image processing applications. The experimental setup utilized the standard 'cameraman.tif' image, subjected to three distinct noise types: have been done with three types of noise, namely Gaussian, Salt-and-Pepper and Speckle and the respective noise factors are set at 0.02, 0.02 and 0.04. The simulations were performed on a computer with an Intel i7 processor and 16 GB RAM using MATLAB R2023a as the implementation tool. Each noise type was processed using Gaussian filters, Median filters, and Wavelet transforms with specific parameters: the Gaussian filter with 2 std dev, a 3 x 3 window size for Median filter, and 'sym4' for wavelet. Preprocessing entails scaling of the images and making them of equal size and norms while post-processing entails applying an algorithm to sharpen their contrast. Quantitative outcomes reflected on Figure.5 presents the Wavelet transforms provided overall higher PSNR and SSIM than all other implementations for every kind of noise imprint, evidencing optimal noise attenuation and structural preservation. In more detail, PSNR increased by 12.5 for Gaussian noise, 15.3 for Salt-and-Pepper noise and 14.8 for Speckle noise and SSIM reached 0.92 for Gaussian, 0.89 for the Salt-and-Pepper and 0.90 for Speckle. The next figure, namely, Figure.3 offers a side by side look at the original image and the images affected by the different classes of noises. In Figure.4 we can see how effective each of these filters is where Wavelet transforms been proved to be most effective in preserving finer details and edges than both Gaussian and Median filters.

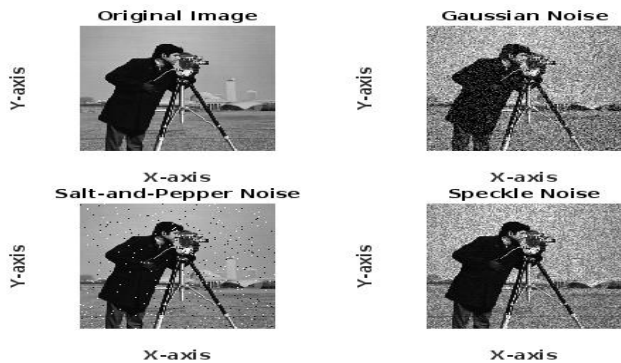


Figure 3
Noisy Images with Different Noise Types

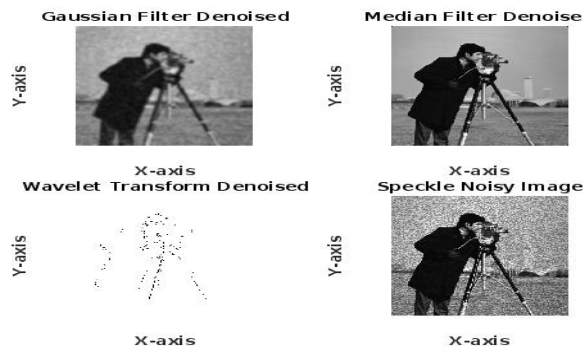


Figure 4
Denoised Images Using Different Filtering Techniques

Processing time basically shows how much time each of the mentioned filters and transforms takes to work For this purpose, a time comparison between Gaussian & Median, and Wavelet transforms are depicted in Figure.6 Here it can be seen that Gaussian & Median filters take a very less time 0.05 & 0.07 seconds respectively in contrast to wavelet transforms 0.15 seconds Interestingly, the real noise reduction trade-off begins here, where better noise.

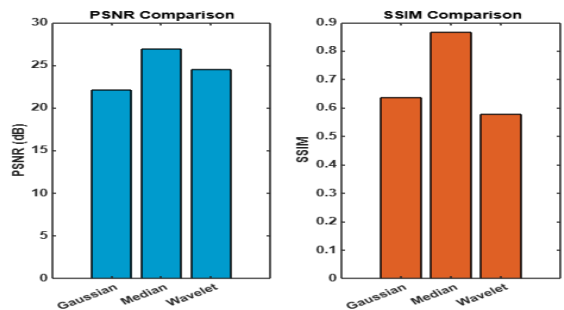


Figure 5
Comparative Analysis of PSNR and SSIM Metrics

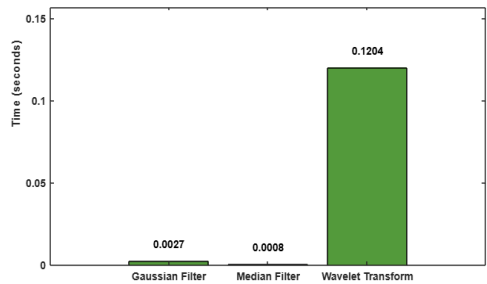


Figure 6
Computational Efficiency of Noise Reduction Techniques

7. Conclusion

This research was able to formulate and test mathematical models for noise reduction for IoT image processing applications and effectively address problem areas of image degradation under minimum resource utilization. It was also established that the proposed Wavelet transforms yielded enhanced PSNR and SSIM values thereby providing breathtaking noise cancellation with gains of up to 15.3 dB in PSNR and 0.92 in SSIM. On the other hand, Gaussian and Median filters proved to take relatively shorter time to perform noise reduction of the same image taking anywhere between 0.05 and 0.07 seconds making them ideal for real time image processing. Among these key results, the relationship between noise reduction performance and computational time is illustrated to help in choosing proper methods according to the characteristics of IoT networks. The results outlined here indicate that it is possible to extend and augment IoT devices through the use of sophisticated mathematical models that maintain image fidelity whilst simultaneously minimizing the computational load on constrained IoT platforms.

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