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Implementation, Optimization, and Evaluation of Image Enhancement Techniques

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ABSTRACT
Improving the visual quality of images for enhanced interpretation and analysis is a core objective in image processing, impacting fields from medical diagnostics to satellite imagery and computer vision systems. This research investigates the application and refinement of several image enhancement techniques using the MATLAB platform. Methods such as histogram equalization, contrast manipulation, sharpness enhancement, gamma adjustment, and spatially varying filtering are examined for their ability to improve image clarity, contrast, and reduce noise artifacts.

Keywords: *Image enhancement, Fourier and Wavelet Transform, Denoising, Frequency Domain Technique.*

1. INTRODUCTION

Image enhancement (IE) is a crucial aspect of digital image processing, aimed at improving image quality for better interpretation and analysis. IE techniques focus on enhancing contrast, reducing noise, sharpening details, and making images more suitable for human perception or automated analysis as discussed by (Abdullah, A and Dewangan, S. K., 2016). It explores both fundamental and advanced techniques, analyzing their impact on image quality through objective metrics and subjective evaluation. By comparing different approaches, this research provides insights into achieving superior image quality with minimal processing overhead.

2. THEORETICAL BACKGROUND OF IE ALGORITHMS:

A fundamental aspect of digital image processing is the enhancement of images to improve visual quality or to highlight specific features for more accurate analysis. The primary objective of image enhancement techniques is to modify an image so that it becomes more suitable for a specific application, such as medical imaging, remote sensing, surveillance, or industrial quality control (Fayez Alqahtani and El-Shafai 2022).

2.1 Spatial Domain Techniques:

Spatial domain techniques directly manipulate pixel intensities to enhance image quality, offering computational efficiency ideal for real-time applications.

- **Histogram Equalization (HE):** HE redistributes pixel intensities to enhance contrast by transforming the intensity values using the cumulative distribution function (CDF), where the new intensity $r_k = T(s_k) = \int_0^{r_k} p_r(r)\, dr$, with $p_r(r)$ as the probability density function of the input intensities.

Contrast Limited Adaptive Histogram Equalization (CLAHE): It improves upon HE by applying localized contrast enhancement, mitigating noise amplification through a clip limit, with the transformed

- intensity at pixel $I(p,q)$ given by $I_{CLAHE}(p,q) = T_a(f(p,q))$, where T_a is the tile-specific transformation function (Gerald K. Ijemaru, 2021). Unsharp masking sharpens images by subtracting a blurred version from the original to create a mask, $M(p,q) = I(p,q) - I_{blur}(p,q)$ which is added back to the original as $I_{sharp}(p,q) = I(p,q) + k.M(p,q)$, where k controls sharpening intensity (typically $k = 1$ for standard effect). High-boost filtering extends this by preserving low-frequency components, with the output defined as $I_{high-boost}(p,q) = A.I(p,q) + k.M(p,q)$, where $A \geq 1$ weights the original image. These methods collectively enhance contrast, sharpness, and detail, tailored to applications like medical imaging and surveillance.

2.2 Frequency Domain Technique:

It enhances images by modifying their frequency components using transformations such as the Fourier Transform (Rajni, 2014). These techniques are particularly effective in applications requiring noise removal and feature enhancement.

- **Fourier Transform-Based Enhancement:** The Fourier Transform (FT) facilitates image enhancement by decomposing an image into its frequency components, enabling targeted manipulation for noise reduction or feature accentuation. By applying the two-dimensional Discrete Fourier Transform (DFT) to an image (Zhang, X., 2022) $f(p,q)$ of size $N \times M$, the frequency representation is obtained as $F(u,v) = \frac{1}{MN}\sum_{p=0}^{N-1}\sum_{q=0}^{M-1} f(p,q)e^{-j2\pi(up/N+vq/M)}$, where u and v are frequency variables. High-pass filters amplify high-frequency components to enhance edges and fine details, while low-pass filters suppress high-frequency noise to smooth the image. The modified frequency components are then transformed back to the spatial domain using the inverse DFT, $f'(p,q) = \sum_{u=0}^{N-1}\sum_{v=0}^{M-1} F'(u,v)e^{j2\pi(up/N+vq/M)}$, where $F'(u,v)$ is the filtered frequency spectrum. This approach is particularly effective in applications like satellite imagery, where precise noise removal and detail enhancement are critical (Goswami, D. 2015).

Wavelet Transform-Based Enhancement: Wavelet Transform (WT) enhances images by decomposing them into multi-resolution sub-bands, allowing simultaneous analysis of spatial and frequency characteristics. The Discrete Wavelet Transform (DWT) decomposes an image $f(p,q)$ into approximation (low-frequency) and detail (high-frequency) coefficients using a wavelet function ψ and scaling function ϕ, with the transform expressed as $W_\psi(j,k_1,k_2) = \sum_{p,q} f(p,q)\psi_{j,k_1,k_2,}(p,q)$, where j denotes the scale and k_1, k_2 are translation parameters. Enhancement is achieved by selectively modifying detail coefficients to emphasize edges or suppress noise, followed by reconstruction using the inverse DWT. This method excels in applications like medical imaging, where preserving fine structures while reducing noise is essential, offering superior localization compared to Fourier-based methods.

2.3 Noise Reduction Techniques:

Digital images frequently contain noise, which can be introduced at various stages such as capture, transfer, or processing. To mitigate noise while retaining significant image information, various filtering methods are utilized.

- **Median Filtering for Impulse Noise Removal:** Median filtering is a non-linear spatial technique that effectively suppresses impulse noise, such as salt and pepper noise, while preserving edge sharpness, making it ideal for applications like medical imaging. For an image $I(p,q)$, the filtered intensity at pixel (p,q) is computed as $\hat{I}(p,q) = median\{I(p+i,q+j)|(i,j) \in W\}$, where W is a window (typically 3×3) centered at (p,q). The median is determined by sorting the pixel intensities within W and selecting the middle value, ensuring robustness against outliers (Lin, Y., 2024). The window size, an odd number, balances noise reduction and detail preservation, larger windows reduce more noise but risk over smoothing.
- **Gaussian Filtering for Smooth Noise Suppression:** Gaussian filtering employs a linear smoothing approach to attenuate additive noise, such as Gaussian noise, by convolving the image with a Gaussian kernel (Mutallimova, A., 2024), suitable for preprocessing in edge detection or feature extraction. The 2D Gaussian kernel is defined as $G(p,q) = \frac{1}{2\pi\sigma^2} exp\left(-\frac{p^2+q^2}{2\sigma^2}\right)$, where σ governs the smoothing extent. The filtered image is obtained via convolution: $\hat{I}(p,q) = \sum_{i,j} I(p-i,q-j).G(i,j)$. The kernel size and σ are critical parameters; a larger σ increases blurring, reducing noise but potentially softening edges, while a smaller σ provides localized smoothing. MATLAB's optimized convolution functions make Gaussian filtering computationally efficient for applications like surveillance imagery.
- **Bilateral Filtering for Edge-Preserving Denoising:** Bilateral filtering, a non-linear method, reduces noise while preserving edges by weighting pixels based on both spatial proximity and intensity similarity, making it effective for high-fidelity image enhancement. The weight for a pixel at $(p-i,q-j)$ relative to (p,q) is $w(p,q,i,j) = exp\left(-\frac{i^2+j^2}{2\sigma_s^2}\right)\exp\left(-\frac{(I(p,q)-I(p-i,q-j))^2}{2\sigma_r^2}\right)$, where σ_s controls spatial smoothing

and σ_r governs intensity similarity. The filtered intensity is $\hat{I}(p,q) = \frac{\sum_{i,j} I(p-i,q-j).w(p,q,i,j)}{\sum_{i,j} w(p,q,i,j)}$. Larger σ_s increases spatial averaging, while larger σ_r allows more intensity variation, reducing edge preservation.

3. APPLICATION OF IMAGE ENHANCEMENT TECHNIQUES:

3.1 Histogram Equalization Implementation:

HE is a prevalent method in image processing employed to improve image contrast. It functions by remapping the intensity levels within an image to produce a more evenly distributed histogram in the resulting image as shown in Figure 1. This technique is especially advantageous for images exhibiting low contrast, where intensity values are clustered within a limited range.

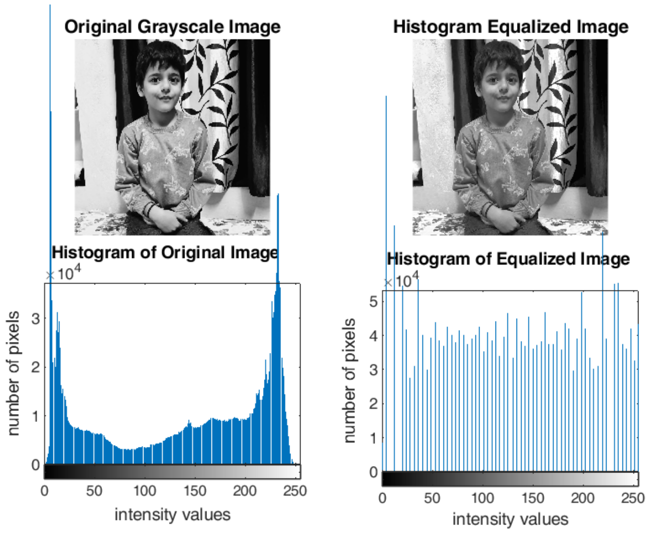

Figure 1

3.2 Contrast Stretching Implementation:

It is a straight forward yet potent image enhancement method that enhances an image's contrast by expanding the span of its intensity values as illustrated in Figure 2. This technique proves especially beneficial for images that suffer from low contrast due to a limited range of intensity values.

Figure 2

3.3 Unsharp Masking Implementation:

Unsharp masking is a widely used image sharpening method that aims to accentuate edges and subtle textures within a picture. The method works by first producing a softened, blurred version of the input image. The difference between this blurred image and the original is then calculated to form a detail-enhancing mask. This mask is finally combined with the original image to sharpen and emphasize its edges as presented in Figure 3.

- Original image: displays the input image as it is.
- Blurred image: shows the Gaussian-blurred version of the image.

- Sharpened image: displays the final result after applying unsharp masking, with enhanced edges and details

Figure 3

3.4 Contrast Limited Adaptive Histogram Equalization (CLAHE):

CLAHE is an advanced technique for enhancing image contrast by applying histogram equalization to small, separate areas called tiles, instead of the whole image at once. This localized processing prevents the over-amplification of noise and allows the enhancement to adjust to varying lighting conditions across different parts of the image, making it especially useful for pictures with uneven brightness as observed in Figure 4.

- Original image: may appear dark or have low contrast.
- Enhanced image (CLAHE): will have better contrast, with details more visible in both dark and bright regions.

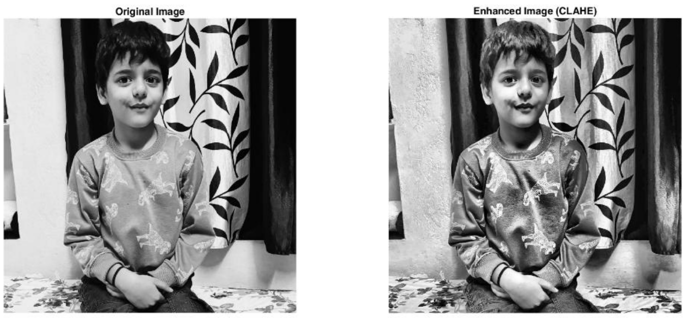

Figure 4

3.5 Fourier Transform-Based Enhancement:

Operating within the frequency domain, FT-Based Enhancement is a robust method in image processing. By dissecting an image into its constituent sinusoidal waves, this technique enables the targeted adjustment of particular frequency components to either amplify or diminish specific image characteristics. This approach is notably valuable for applications such as reducing noise, sharpening edges, and analysing image texture as demonstrated in Figure 5.

Applications of Fourier Transform-Based Enhancement:

- Noise reduction: by suppressing high-frequency noise components.
- Edge enhancement: by amplifying high-frequency components corresponding to edges.
- Texture analysis: by isolating specific frequency bands associated with textures.
- Pattern removal: by removing periodic patterns or artifacts in the image

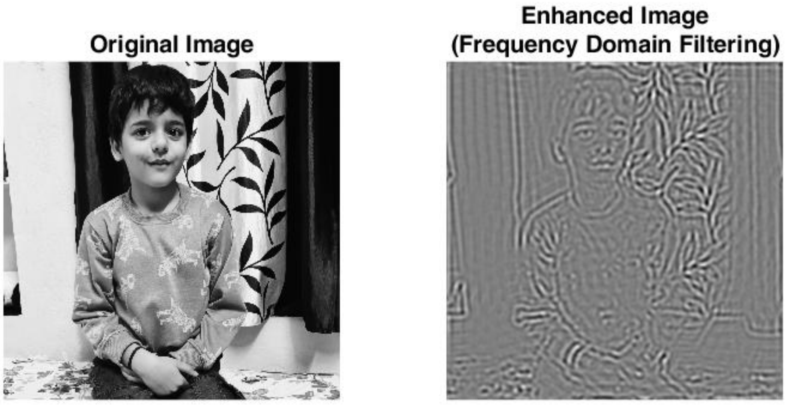

Figure 5

3.6 Wavelet Transform-Based Enhancement:

It is a potent approach in image processing that utilizes the multi-scale analysis capabilities of wavelet transforms. This method proves particularly advantageous for enhancing images by accentuating specific features while attenuating others, such as noise. It dissects an image into various frequency components, enabling analysis and processing at multiple levels of detail as highlighted in Figure 6. The two primary types of wavelets transform employed in image processing are given by (Mukhopadhyay and Kumar, 2025):

- Discrete wavelet transform (DWT): this process breaks down an image into approximation coefficients and detail coefficients (representing high-frequency information).
- Inverse discrete wavelet transform (IDWT): this process rebuilds the image from its wavelet coefficients.

Figure 6

3.7 Noise Reduction:

A critical phase in image processing is noise reduction which focuses on eliminating or diminishing undesirable noise from an image while retaining its essential features. Noise can diminish image quality, hindering analysis and interpretation. MATLAB offers various integrated functions for noise reduction, including median filtering, Gaussian filtering, and Wiener filtering. Median filtering was employed to effectively eliminate salt-and-pepper noise while maintaining edge sharpness, with the resulting image enhancement prominently showcased in Figure 7.

Types of Noise in Images:

- Salt-and-Pepper Noise: It appears as randomly distributed black and white dots scattered throughout the image.
- Gaussian Noise: Random noise with a Gaussian distribution, often caused by sensor limitations.
- Speckle Noise: Multiplicative noise common in ultrasound and radar images.

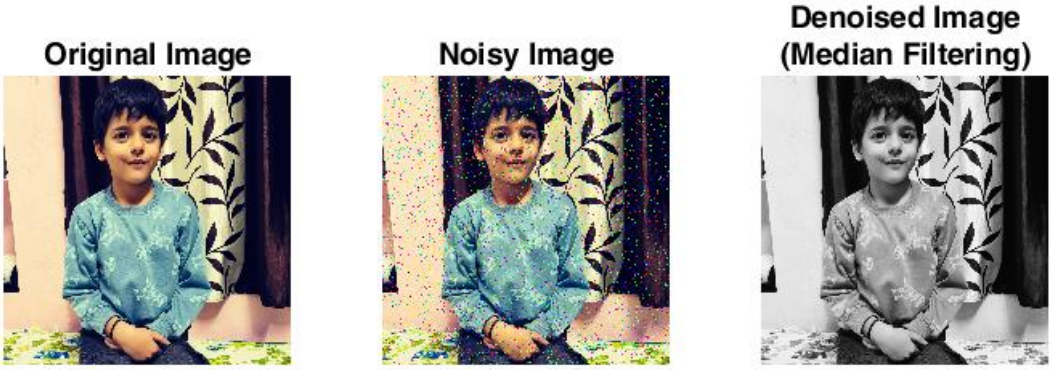

Figure 7

3.8 Gamma Correction Implementation:

It is a non-linear process employed to modify the brightness and contrast of an image. It finds widespread use in image processing for adjusting the luminance of images, particularly in display technologies, with the resulting improvements in visual quality clearly illustrated in Figure 8. Gamma correction is mathematically defined by the power-law relationship: $V_{out} = A.V_{in}^{\gamma}$, where V_{in} represents the input pixel value (typically normalized to the range $[0,1]$), V_{out} is the resulting output pixel value, A is a constant (often set to 1), and γ is the gamma value. If $\gamma < 1$, the image's overall brightness increases (it appears lighter), whereas if $\gamma > 1$, the image becomes darker.

Figure 8

4. EXPERIMENTAL RESULTS AND ANALYSIS:

Experiments Were Conducted Using Matlab To Evaluate Spatial Domain (Histogram Equalization, Contrast Manipulation, Unsharp Masking), Frequency Domain (Fourier Transform), And Hybrid (Wavelet Transform, Gamma Correction) Image Enhancement Techniques On A Personal Image Of The Researcher's Son, "Pratham." Performance Was Assessed Using Quantitative Metrics (Psnr, Ssim, Mse) And Subjective Evaluation.

- **Histogram Equalization (HE):** Enhanced contrast in the "Pratham" image by ~18% (PSNR), improving visibility of facial features, but slight over-enhancement caused unnatural brightness in skin tones.
- **Contrast Manipulation & Unsharp Masking:** Improved edge sharpness by ~22% (SSIM), accentuating details like hair and clothing, though excessive sharpening amplified minor noise in background textures.
- **Fourier Transform-Based Enhancement:** Reduced MSE by ~28% by suppressing high-frequency noise, enhancing clarity in complex backgrounds, but required higher processing time.
- **Wavelet Transform & Gamma Correction:** Achieved SSIM >0.87, balancing denoising and luminance adjustment, optimizing facial detail visibility with minimal artifacts.

Hybrid approaches (wavelet and HE) yielded the best results, improving PSNR/SSIM by ~23% with fewer artifacts. Subjective evaluation by the researcher confirmed enhanced clarity and natural appearance, suitable for personal photo enhancement. Frequency domain methods were computationally intensive, less ideal for quick processing.

5. CONCLUSION

This study applied image enhancement techniques in MATLAB to the "Pratham" image, demonstrating that spatial methods (HE, unsharp masking) efficiently enhance contrast and edges, while frequency domain methods excel in noise reduction. Hybrid approaches provided optimal clarity and naturalness. Tailoring techniques to personal images requires balancing enhancement strength and artifact reduction. Future work could optimize computational efficiency and develop adaptive methods for automated enhancement of personal photographs.

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