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Enhancement of Digital Images Using Discrete Cosine Transform (DCT): Quality Analysis Based on PSNR and SSIM Metrics

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تحسين الصور الرقمية باستخدام تحويل جيب التمام المنفصل (DCT) وتحليل الجودة باستخدام PSNR و SSIM

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Abstract:
The field of image processing has witnessed significant growth, largely due to the widespread application of digital image processing techniques across various domains. These applications often share a common requirement: the need for methods that enhance pictorial information to facilitate human interpretation and analysis. This study aims to apply a frequency-based enhancement technique to improve distorted digital photographs. One such technique is the Discrete Cosine Transform (DCT), which has demonstrated promising results. The application of this method to grayscale images affected by distortions led to noticeable improvements in overall image quality.

Keywords: Digital Images, Image Enhancement, Discrete Cosine Transform Function.

الملخص:
شهد مجال معالجة الصور نموًا واسعًا، ويرجع ذلك إلى الاستخدام الواسع لأساليب المعالجة الرقمية للصور في مجالات متعددة، حيث تشترك هذه التطبيقات في الحاجة إلى تقنيات قادرة على تحسين المعلومات التصويرية لتسهيل تفسيرها وتحليلها من قبل الإنسان. يهدف هذا البحث إلى تطبيق تقنية تعزيز ترددي على الصور الرقمية المشوّهة. وتُعد دالة التحويل الجيب التمام المتقطع (DCT) إحدى هذه التقنيات التي أظهرت نتائج واعدة. فقد أدى تطبيق هذه الطريقة على الصور الرمادية المشوّهة إلى تحسين ملحوظ في جودة الصورة.

الكلمات المفتاحية: الصور الرقمية، تحسين الصور، دالة التحويل الجيب تمام المنفصل.

Introduction:

Images can be classified into analog and digital images based on the nature of their pictorial representation [1,2]. An image is considered analog if it can be expressed using analog vector formats, while it is considered digital if it can be represented or stored as digital data. Similarly, the field of image processing is divided into two main categories: analog image processing and digital image processing [3,4]. In the context of modern computer science, digital image processing is defined as the processing of digital images through algorithms executed by digital computers. In contrast, analog image processing refers to image processing tasks carried out using two-dimensional analog signals and analog methods.

Since the invention of digital computers, digital image processing has gained several advantages over analog image processing [6-9]. This progress has led to the development of a wide array of techniques and methods in the form of various algorithms applied to image data. These operations may include digitizing images, calibration, and the removal of accumulated noise and distortion during processing. As images are typically defined across two or more dimensions, digital image processing can be modeled as a multidimensional system [8,9]. This field has evolved rapidly due to advancements in computer science and mathematics, along with the practical demand for applications across a broad range of scientific, industrial, and medical domains.

The proposed filter is based on enhancing edge localization in images initially processed by an efficient Principal Component Analysis (PCA) filter [10-12]. This enhancement is achieved through a combination of local pixel grouping, bilateral filtering, and the application of the Sobel operator. In their study, the authors also propose a method for image enhancement and distortion removal utilizing the Discrete Cosine Transform (DCT) [13,14].

Definition:

Digital image processing is a branch of computer science and engineering concerned with the study and application of algorithms used to process images captured or represented in digital form. The primary goals of digital image processing are to enhance image quality, extract useful information, or prepare images for specific applications such as pattern recognition, medicine, engineering, and telecommunications [15].

This field encompasses a wide range of operations, including contrast enhancement, noise reduction, color correction, geometric transformations, and image analysis techniques [16]. These processes are implemented using digital computers, where images are treated as matrices of pixels. Various mathematical algorithms are applied to these pixel arrays to achieve specific objectives, whether to improve the visual appearance of the image or to extract meaningful data from it [17].

Moreover, the primary objective of image enhancement techniques is to process an image in a way that makes the resulting image superior to the original in terms of quality or clarity, according to the requirements of a specific application. Image enhancement methods are generally classified into two main categories**:** "spatial domain methods" and "frequency domain methods" [18].

The spatial domain refers to direct manipulation of the pixels in an image, where enhancement operations are applied directly to the intensity values of the image. On the other hand, frequency domain methods involve transforming the image from the spatial domain into the frequency domain using mathematical transformations such as the Fourier Transform or the Discrete Cosine Transform (DCT) applying the enhancement in the frequency space, and then transforming the image back to its original domain [19]

Definition:

Spatial domain image enhancement techniques refer to methods that directly manipulate the pixel values of an image to improve its visual quality or extract useful information 19 The term "spatial domain" denotes the physical space in which the image elements (pixels) are located, and the enhancement process operates directly on these elements. Mathematically, spatial domain processing can be represented as:

$$f(u, v) = T[g(u, v)] \quad (1)$$

Where:

- $g(u, v)$ represents the original input image,
- $f(u, v)$ denotes the enhanced output image,
- T is a transformation function applied to the pixel at coordinates (u, v) based on a defined neighborhood.

The transformation function T can be designed to process individual pixels or operate over a set of neighboring pixels, typically arranged in a square or rectangular region centered at (u, v). This neighborhood region moves across the image from one pixel to the next, usually starting from the top-left corner, applying the transformation to generate the enhanced output [20]. In some cases, T may incorporate information from multiple input images, allowing for operations such as pixel-by-pixel averaging to reduce noise. While alternative neighborhood shapes, such as circular regions, are occasionally used, square and rectangular regions remain the most common due to their simplicity and computational efficiency. A common technique within this domain involves the use of masks, templates, or filter windows, which are typically small matrices (e.g., 3×3) that define the weights or operations to be applied to each pixel within the neighborhood during the enhancement process [21].

Therefore, in frequency domain image enhancement, filtering is performed by manipulating the frequency components of an image. The primary concept involves allowing certain frequency components to pass through (i.e., be retained) while suppressing or eliminating others that are considered unwanted or detrimental to image quality. This process relies on a "filter transfer function", denoted as H (x, y), which defines how each frequency component is modified. The original image is first transformed from the spatial domain to the frequency domain typically using transformations such as the Discrete Cosine Transform resulting in a frequency representation of the image, denoted by F (x, y) [19-21]. The enhanced image is obtained by applying the filter function to the transformed image, and then performing an inverse transformation to return to the spatial domain. Mathematically, the enhanced image is given by:

$$G(x, y) = H(x, y) \times F(x, y) \qquad (2)$$

Where:

- F (x, y) is the frequency representation of the original image,
- H (x, y) is the filter transfer function,
- G (x, y) is the modified frequency domain representation of the image.

Finally, applying the inverse Discrete Cosine Transform to G(x, y) yields the enhanced image in the spatial domain.

The Discrete Cosine Transform (DCT):

The method proposed in this study is an algorithm for enhancing the plain, noisy image using DCT, and its steps are as follows [22-24].

- Divide the input image into 8x8 blocks1.
- Calculate the discrete cosine transform (DCT) for each block according to the following equations.
- Zero out the elements below the main diagonal.

$$B_{pq} = \alpha_p \alpha_q \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} A_{mn} cos \frac{\pi(2m+1)p}{2M} \, cos \frac{\pi(2n+1)q}{2N}$$

$$0 \le p \le M-1 \qquad 0 \le q \le N-1$$

$$\alpha_p = \begin{cases} 1/\sqrt{M} & , p = 0 \\ \sqrt{2/M} & , 1 \le p \le M-1 \end{cases}$$

$$\alpha_p = \begin{cases} 1/\sqrt{N} & , q = 0 \\ \sqrt{2/N} & , 1 \le q \le N-1 \end{cases} \qquad (3)$$

- Find the inverse discrete cosine transform (IDCT) for each of the blocks as follows:

$$A_{mn} = \alpha_p \alpha_q \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \alpha_p \alpha_q \, B_{pq} cos \frac{\pi(2m+1)p}{2M} \, cos \frac{\pi(2n+1)q}{2N}$$

$$0 \le m \le M-1 \qquad 0 \le n \le N-1$$

$$\alpha_p = \begin{cases} 1/\sqrt{M} & ,p = 0 \\ \sqrt{2/M} & ,1 \leq p \leq M-1 \end{cases}$$

$$\alpha_p = \begin{cases} 1/\sqrt{N} & ,q = 0 \\ \sqrt{2/N} & ,1 \leq q \leq N-1 \end{cases} \quad (4)$$

- Reassemble the image.

Quality Assessment Criteria for Digital Images

Peak signal-to-noise ratio PSNR:

This measure, which is based on the peak signal-to-noise ratio, is effective at processing images and reducing noise. It is also good at preserving edges and corners, based on the following equation [25-27]:

$$PSNR = 10\ log_{10}\left[\frac{255^2}{\frac{1}{MN}\sum_i \sum_j (r_{ij} - x_{ij})^2}\right] \quad (5)$$

Where r_{ij} andx_{ij} represent the element values of both the original and processed images, and MN represents the image size.

Structural Similarity Image Quality Measure (SSIM):

The measurement is determined by assessing three different topics: luminance, contrast, and comparing the general structure [28-30].

$$l(u,v) = \frac{2\mu_u(u,v)\mu_v(u,v) + C_1}{\mu_u^2(u,v) + \mu_v^2(u,v) + C_2} \quad (6)$$

$$c(u,v) = \frac{2\sigma_u(u,v)\sigma_v(u,v) + C_1}{\sigma_u^2(u,v) + \sigma_v^2(u,v) + C_2} \quad (7)$$

$$s(u,v) = \frac{\sigma_{uv}(u,v) + C_3}{\sigma_u(u,v)\sigma_v(u,v) + C_3} \quad (8)$$

$$SSIM(u,v) = [l(u,v)][c(u,v)][s(u,v)] \quad (9)$$

where, $l(u,v)$is the luminance or brightness, $c(u,v)$ is the contrast, as for $s(u,v)$ it is the structural similarity.

Universal Quality Index (UQI):

The evaluation metric consists of three main components. The first component is the correlation coefficient between the original and distorted images on one hand, and the restored image on the other. This coefficient quantifies the degree of linear relationship between the compared images, with a dynamic range extending from −1 to 1. A value closer to 1 indicates a stronger positive linear correlation. The second component evaluates the similarity in mean luminance (average brightness) between the original and the restored image. Its range lies between −1 and 0, and it achieves its maximum value of 1 when the mean values of the two images are identical. This component provides an indication of how well the average intensity is preserved during restoration [31-33].

The third component measures the similarity in contrast between the two images. It is calculated based on the standard deviations of the images and ranges between 0 and 1, where a value of 1 indicates perfect contrast similarity. By combining these three components correlation, luminance similarity, and contrast similarity a comprehensive quality assessment metric is obtained. The resulting overall measure is often expressed through a specific formula that integrates these factors to quantify the degree of similarity between the original and restored images:

$$UQI = \frac{4\,\bar{I}\bar{I}_n\sigma_{IIn}}{(\bar{I}^2 + \bar{I}_n^2)(\sigma_I^2 + \sigma_{In}^2)} \quad (10)$$

where, σ_I, σ_{In} Standard deviation of the original and distorted image.
$\bar{I}$, $\bar{I}_n$ Average for the original and processed image.
σ_{IIn} Covariance.

Analysis and Discussion of Experimental Results:

To evaluate the effectiveness of the digital image enhancement process, Gaussian noise was artificially introduced to the original image at varying levels, including a baseline level of 0% and a higher level of 10%, resulting in a set of distorted images. The proposed enhancement method was then applied using the Discrete Cosine Transform **(**DCT**)** to reduce the noise and improve image quality. To objectively assess the performance of the enhancement technique, several reference image quality metrics were employed, including Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index Measure **(**SSIM**)**, and Universal Quality Index **(**UQI). These metrics were used to quantify the degree of improvement achieved and to compare the results against standard benchmarks. The experiments were conducted using standard grayscale digital images with dimensions of 256 × 256 pixels, which are commonly used in image processing research for performance evaluation and comparison, namely images (1) and (2).

Experiment 1:
Input: Normal image 1 containing distortions (noise).
Outputs: The improved image after applying the proposed method, which shows the relationship between the quality criteria (PSNR, UQI, SSIM).



(A) (B) (C)

where: A is the original image (1).
B is the noisy image with PSNR=20.3419, SSIM=0.4279, UQI=0.3127.
C is the enhanced image using the proposed method (DCT) with PSNR=22.4330, SSIM=0.5249, UQI=0.3415.

Experiment 2:
Input: Normal image 2 containing distortions (noise).
Outputs: The improved image after applying the proposed method, which shows the relationship between the quality criteria (PSNR, UQI, SSIM).



(A) (B) (C)

whereas: A is the original image (1).
B is the noisy image with PSNR=20.0609, SSIM=0.4404, UQI=0.3844.
C is the enhanced image using the proposed method (DCT) with PSNR=22.2740, SSIM=0.5406, UQI=0.4380.

Conclusion:

The proposed frequency-domain image enhancement method has demonstrated its effectiveness in improving image quality by leveraging the characteristics of the high-frequency components located below the main spectral band of the image. These components typically represent small variations often imperceptible to the human eye and are frequently associated with noise. By attenuating or eliminating these components, the algorithm enhances the image while preserving perceptual quality. Quantitative evaluation of the enhanced images revealed an increased Peak Signal-to-Noise Ratio (PSNR), indicating a notable reduction in distortion and an improvement in overall image fidelity. In addition, both the Structural Similarity Index Measure (SSIM) and the Universal Image Quality Index (UIQ) values were higher for the enhanced images, suggesting a stronger resemblance to the original undistorted image. These results confirm that the proposed algorithm not only reduces noise and distortions but also preserves structural and perceptual details more effectively than the distorted input.

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