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Advancements in Image Compression Techniques: A Comprehensive Review

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Abstract—

Image compression is crucial for shrinking the size of digital photos without reducing quality. The demand for storage and bandwidth capacity continues to exceed available capacity, making image compression a necessary technique. The article compares and contrasts a number of lossy and lossless image compression methods, including Wavelet coding, transform coding, Run length coding, Huffman encoding, and Arithmetic coding. The study makes broad recommendations for identifying the best compression strategy for an image. The primary benefits, drawbacks, and research opportunities of these techniques are discussed to aid in selecting the appropriate compression method. The article concludes by stating that image compression is an essential technique that enables faster file transfer, storage optimization, and efficient use of physical storage resources.

Keywords— Image Compression; Image; Huffman encoding; Arithmetic coding; Lossy compression; Quality preservation; Data reduction.

I. INTRODUCTION

Image compression is an essential technique that encodes an image with fewer bits and stores or transmits it in an efficient form Pixels are placed in a matrix or array with columns and rows to represent images. This method that minimizes an image's data size without reducing its quality is known as image compression. The compressed image requires less storage space and can be transmitted over networks more quickly than the original image. There are various algorithms for compressing images, both lossless and lossy. Lossless compression techniques preserve the similar data as the original image, while lossy compression results in some data loss. Some compression methods are aimed for specific kinds of images, and adjusting their parameters can improve the compression ratio. Lossless compression techniques preserve all the data of the original image, while lossy compression techniques sacrifice some information to achieve higher compression ratios. The choice of compression methods which relay on the conditions of the application, such as image quality, compression ratio, and computational complexity. This work provides an overview of various picture compression algorithms and their goals, highlighting both their benefits and drawbacks.

II. LITERATURE REVIEW

[1] The concept of Sub- Coding is accomplished by dividing the input data into tiny bands., which are then decimated and coded independently. A tree-type filter system requires allowing the input signal to be divided into more than two bands in order to review the earlier procedure. The implementation of two-dimensional QMF sieve methods to digital image sub-band coding has been studied in this instance, the I and Q signals were low-pass refracted while the lowest band underwent DPCM coding and a 16-to-1 15-level decimation amplifier. The monochromatic signal spectrum's lowest band was DPCM classified during the coding process using a two-dimensional projection and a 31-level nonuniform d quantizer. The luminance signal was considered the same as monochrome images, but the upper band signals for the 1 and Q components were ignored.

[2] Both memory space requirements and higher picture quality attributes, both of which are crucial for image analysis, will be considered while analysing a good image. Compression essentially implies deleting unneeded information from an image, which merely increases memory space requirements without impacting image quality. The Huffman coding technique aims to simplify and improves image compression. The image has as to be compressed is obtained merging matrices. The author of this research uses MATLAB to simulate a quick and enhanced Huffman image compression approach. Under this study, the findings further showed that the

Huffman image compression coding methodology doesn't somehow perform for multi-order images. The PSNR graph shows that a light image has a higher PSNR than a dark image.

[3] Since it analyses signals in both the temporal and frequency domains, Wavelet transform 4 was introduced, For image deflating, this proposition associates “hybrid wavelet transform” (HWT) and “vector quantization” (VQ). To improve the compression ratio, the vector quantization approach used. Using altered photos, the LBG, KMCG, and KFCG VQ algorithms are used to build 16 and 32-size codebooks. By compressing the rebuilt picture acquired at the ratio of 32 in hybrid wavelet transform, the maximum compression ratio of 153.6 is reached. At this compression ratio, a blocking effect is detected, which downsize image features, and show remodelled images after applying the LBG, KMCG, and KFCG algorithms to the transformed image and generating codebook size 16 and show remodelled images when codebook size 32 is developed based on VQ algorithms LBG, KMCG, and KFCG. The VQ algorithms LBG, KMCG, and KFCG are employed. In this instance, the compression ratio is increased to 192 and 153.6, respectively, by the creation of code vectors 16 and 32. Both KMCG and KFCG offer high-quality photos with compression ratios up to 192 and are quicker to perform.

[4] Lossy compression techniques cause data loss with higher compression ratios, whereas lossless compression gives outstanding image quality but only uses a little amount of compression. Several picture compressions approaches, such as BTC and AMBTC, have been presented over the previous two decades. AMBTC keeps the blocks' upper and lower means and uses this quantity to quantize output. Section VI introduces the experimental results, and Section VII concludes. Both methods separate the image into non-overlapping chunks and employ a two-level quantize. Image quality was assessed using objective metrics such as. At the same bit rate, image compression using AMBTC gives greater image standards than image compression using BTC.

[5] Linear algebra is used extensively in data compression.

The factorization of A into ‘U’ ‘V’ ‘T’, where U and V are orthonormal matrices, is known as SVD. It is a diagonal matrix made up of A's singular values.

U is originally a m*m matrix, but only the first k columns are needed.

This suggests that U can be represented by a m k matrix with mk values.

“UM = mk” Similarly, only store V is to be stored as a n k matrix with nk values if just the first k columns are needed.

“VM = nk” Yet, this leads A M, the "compressed" image, to consume more space than the original image, completely undermining the objective of SVD compression. This means that the k for which SVD truly saves memory has important constraints.

III. CLASSIFICATION OF COMPRESSION ALGORITHM

Image compression techniques are Basically classified into two major types based on the requirements.

1) LOSSLESS IMAGE COMPRESSION TECHNIQUES:

A method for shrinking an image file's size without losing any information is called "lossless image compression." In lossless image compression, the compressed file can be decompressed to the exact same original image file. This makes it ideal for applications where the image data must remain unchanged, such as medical imaging and scientific research. There are various lossless picture compression methods that each have their own pros and cons.

A) Run-length Encoding (RLE)

Through the implementation of this data compression method, the size of the data was reduced without any data being lost and by encoding consecutive runs of identical values as a single value and count. It is commonly used for compressing simple data such as images, audio signals, and text files. In RLE, a sequence of consecutive identical values is compensated with a single value and repeatedly appears in the sequence. RLE is a simple and fast compression method that can achieve high compression ratios for data with long runs of identical values. However, it may not be effective for compressing complex data or data with short runs of identical values. Moreover, the compressed data size may increase if the original data has no consecutive runs of identical values. RLE is widely used in various applications, including image and audio compression, text compression, and data transmission over low-bandwidth channels. To further minimise the amount of the compressed data, it is often used in conjunction with other compression methods like Huffman coding or arithmetic coding. The picture is read through either column by column or row by row. Consecutive runs of identical pixels are identified, and each run is encoded as a single value and count. This means that instead of storing every pixel individually, the compressed image stores the value of a pixel and the number of times it appears consecutively. This compression method is particularly effective for images with long runs of identical pixels, as it can achieve high compression ratios.

B) Huffman Encoding

Huffman coding is a lossless data compression technique based on the probability distribution of pixel values in an image. It involves calculating the frequency distribution of pixel values in the image, which is then used to determine the likelihood distribution. After the possible outcomes are revealed, code words are assigned based on the likelihood value, with higher probability values assigned shorter codes and lower probability values assigned longer codes. As an outcome, the pixel values are encoded more effectively. To create a Huffman code for a given attributes and their probabilities, a binary tree is generated by combining the symbols with the minimum likelihood from left to right. The process involves adding the probabilities of the two symbols and creating a new node with this sum as its probability. As long as there is just one node left, representing the whole symbol set, this procedure is repeated. Finally, bits are allocated to the binary tree's branches beginning at the root and moving right to left. Huffman coding is particularly effective for images with a high degree of redundancy in their pixel values. It can minimise image quality by up to 50% without affecting quality.. However, it can be less effective for images with complex or irregular distributions of pixel values, as the code words may not be optimally assigned.

Implementing reliable methods, which include Huffman coding and arithmetic coding for lossless compression and JPEG and MPEG for lossy compression, is essential to achieve reliability in image compression. These techniques significantly reduce data size while preserving image quality, laying the foundations for robust compression. These techniques are being improved by ongoing research in these areas, ensuring accurate and efficient image compression for a variety of applications.

C) Arithmetic Coding

This statistical coding method called arithmetic coding replaces each sequence of symbols with a single fractional integer. Unlike Huffman coding, arithmetic coding does not require the use of fixed-length codes, and it can achieve higher compression ratios by assigning shorter codes to more frequent symbols. To encode an image, arithmetic coding divides the image into a series of non-overlapping intervals or ranges, each corresponding to a symbol or a combination of symbols. The size of every iteration is determined by the probability of occurrence of the corresponding symbol or symbol combination. A single compressed picture is shown by a single fractional number that falls within the range of the final interval. To decode the image, the fractional number is converted back into the corresponding symbol sequence using the same probability distribution. Arithmetic coding is particularly effective for compressing images with a large number of colours or shades of grey, where Huffman coding becomes less efficient.

D) Lempel-Ziv-Welch (LZW) Encoding:

Lempel-Ziv-Welch (LZW) encoding is a lossless compression technique that uses a dictionary to encode repeating patterns in the image. The technique works by building a dictionary of patterns encountered in the image and assigning a unique code to each pattern. Whenever a repeating pattern is found, it is replaced with the corresponding code from the dictionary. This reduce the data that needs to be stored or transmitted. LZW encoding is particularly effective for images that contain repetitive patterns, such as graphics and text. As the dictionary grows, the compression ratio also improves. However, for images with a low degree of repetition, the compression ratio may not be as high. LZW encoding has been widely used in image file formats such as GIF, TIFF, and PDF, and has become one of the most popular lossless compression techniques for digital images.

2) LOSSY IMAGE COMPRESSION TECHNIQUES:

Lossy compression techniques are used to reduce the size of an image by removing some of its information that may not be critical to its quality or interpretation. These methods are employed when storage capacity or transmission bandwidth are restricted. Unlike lossless compression, lossy compression algorithms do not guarantee the exact reconstruction of the original image from the compressed data. The level of compression used on the image determines how much data is lost. The following are the most popular lossy picture compression methods:

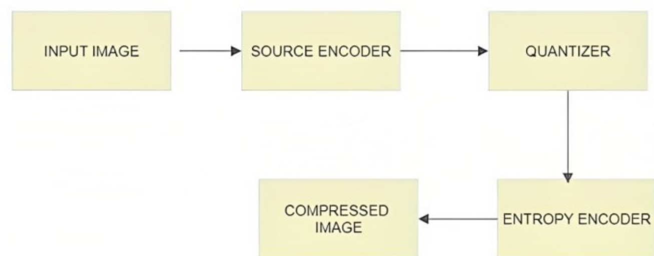
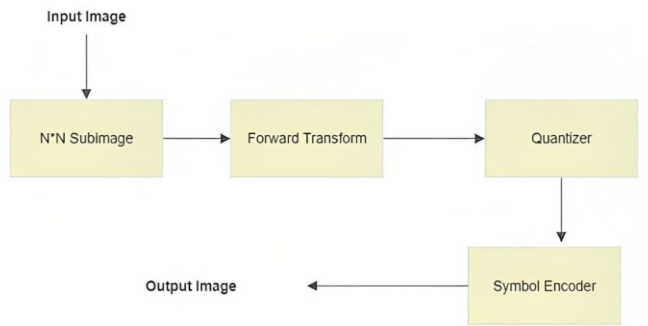


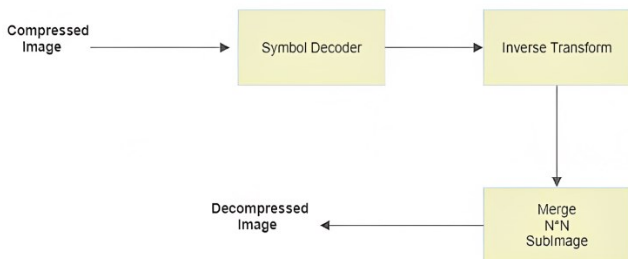
Figure 1. Block Diagram for Lossy Compression

1) TRANSFORM CODING:

Using mathematical transformations like the Discrete Cosine Transform (DCT) [1] or the Wavelet Transform, the picture is transformed from the spatial domain to the frequency domain in the lossy compression method known as "transform coding." An array of coefficients that characterise the frequency content of the picture serve as the image's representation in the frequency domain. The high-frequency components of the image, which represent the details and noise, are often discarded or reduced in magnitude, as they are less perceptually important than the low-frequency components that represent the image's structure and overall appearance. This reduction of high-frequency components helps to achieve a higher compression ratio by removing less important information from the image. This method is used for Image and video compression standards. The technique allows for efficient compression with minimal loss of perceptual image quality. However, the amount of compression that can be achieved is limited by the transform used and the degree of lossy compression applied.



[A] Encoding Process



[B] Decoding process

Figure 2. Transform Coding

2) DISCRETE COSINE TRANSFORM:

This lossy compression technique that converts a block of pixel data into a set of frequency coefficients. Image and video compression used widely in applications such as RAW, GIF, JPEG, PSD MPEG, and H.264. Discrete Cosine Transform (DCT) works by decomposing the image into a set of frequency components, where high-frequency components represent finer details and low-frequency components represent larger features in the image. The DCT algorithm performs a mathematical transformation on a block of pixel data to create a set of frequency coefficients. The DCT is applied to each block of pixel data, and the resulting coefficients are quantized to lower the amount of data essential to depict the image. Quantization process involves rounding the factors to the nearest integer value, with smaller values representing more important details in the image. Since the DCT is a lossy compression technique, some of the information in the original image is lost during the compression process. The amount of compression achieved using DCT can be restricted by modifying the quantization step size. Smaller step sizes result in higher-quality compressed images but larger file sizes, while larger step sizes result in lower-quality compressed images but smaller file sizes.

3) VECTOR QUANTIZATION:

Vector Quantization (VQ) is a lossy image compression technique that uses scalar quantization principles in multiple dimensions. In VQ, a codebook or dictionary of fixed-size vectors is created for encoding the image. The image is divided into non-overlapping chunks, with the closest matching vector from the codebook replacing each block. The index of the closest matching vector is used to represent the block in the compressed image. The VQ technique is advantageous in multimedia applications because it allows for efficient decoder-side searching. It achieves compression by creating a codebook of fixed-size vectors and using scalar quantization principles in multiple dimensions to replace image blocks with the closest matching vector from the codebook. VQ has a high computational cost due to the need to search for the closest matching vector in the codebook for every image block.

4) FRACTAL COMPRESSION:

"Fractal compression" is one of the lossy image compression techniques that uses the principles of fractal geometry to compress image data. Fractals are mathematical patterns that can be generated by repeating a simple process multiple times, resulting in complex and detailed structures. In the context of image compression, fractal compression uses self-similarities in an image to compress it. The underlying idea of fractal compression is to signify a picture as a sequence of modifications done to a tiny section of the image termed a "domain block". The domain block is then iteratively transformed to generate a larger image. These changes are performed using affine transformations such as translation, scaling, and rotation. Fractal compression works by finding a set of transformations that will result in a slight variation between the flattened image and the original image. This is achieved by comparing the domain block with larger portions of the image, searching for areas that are similar to the domain block. Once a similar area is found, the transformation that maps the domain block to the larger area is recorded and used to generate the compressed image. The main advantage of fractal compression is its ability to accomplish high compression ratios asserting the image quality. This is because fractals can represent complex images with a small amount of data, by encoding the self-similarities in an image. However, fractal compression is computationally intensive and can require a significant amount of processing power and time to compress an image. It is also a patented technology, which limits its use in commercial applications.

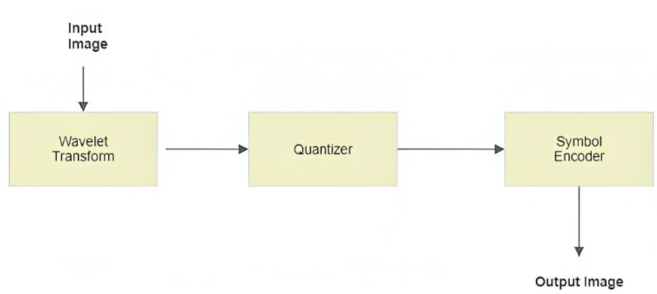
5) SINGULAR VALUE DECOMPOSITION:

Singular Value Decomposition (SVD) is a factorization methodology used to decompose a matrix into its factors wedge so that various operations can be performed on the matrix. [5] It's popular in data analysis and machine learning applications. In SVD, a matrix A is decomposed into three matrices: U, Σ, and V, such that A = UΣV^T, where U and V are orthogonal matrices and Σ is a diagonal matrix containing the singular values of A. The singular values represent the strengths of the underlying patterns in the data, with larger values indicating more important patterns. [5] The U matrix contains the left singular vectors of A, which represent the directions of maximal variability in the data. The V matrix contains the right singular vectors of A, which represent the directions of maximal correlation between the columns of A. The Σ matrix contains the singular values of A, which represent the magnitudes of the singular vectors. SVD has many applications, including data compression, image processing, and collaborative filtering. It is particularly useful in recommender systems, where it can be used to predict user ratings for items based on their past ratings and those of similar users. SVD also has several interesting mathematical properties. For example, it can be used to find low-rank approximations of a matrix, which can be useful in reducing the dimensionality of high-dimensional data. Additionally, SVD can be used to solve linear systems of equations and to perform principal component analysis (PCA) on a dataset.

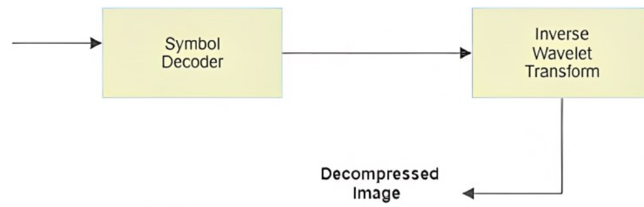
6) WAVELET CODING:

Wavelet coding is a robust compression technique used for reducing the size of digital data, photos, or movies is wavelet coding. With the aid of a wavelet transform to analyze the signal at various scales or resolutions, it uses wavelets, or localized waveforms, to describe larger signals. This signal's numerous components may be represented at varying degrees of detail attributable to the wavelet breakdown. Wavelet coding reduces the quantity of data while maintaining its contents by rejecting less important wavelets and keeping the most important ones. Notably, wavelet coding works better than other compression methods like JPEG or MPEG because it better preserves depict features and edges that could be lost in other techniques.

For significant size reduction, it is frequently used as a pair with other methods like Huffman coding or arithmetic coding. However, current work in this area emphasizes on improving existing algorithms and investigating cutting-edge ideas, such as deep learning-based methods, to obtain even greater compression ratios without sacrificing image quality. The topic of image compression is being advanced for several real-world uses with regard to the ongoing development and comprehension of wavelet-based methods to compress images.



[A] Encoding Process



[B] Decoding process

Figure 3. Wavelet Coding

IV. CONCLUSION

In conclusion, this research has shed light on the critical role of image compression in the domain of digital signal processing. By emphasizing the trade-offs between compression ratio and image quality, it highlights the need for careful consideration when selecting the most appropriate compression techniques. Advanced methods such as deep learning-based approaches and wavelet coding show promising results in achieving higher compression ratios while maintaining superior image quality. Ongoing research efforts aim to enhance the efficiency and effectiveness of these techniques, addressing their limitations and refining their performance. By implementing reliable methods like Huffman coding and arithmetic coding for lossless compression, and JPEG and MPEG for lossy compression, practitioners can achieve reliable image compression while optimizing storage and transmission. The insights provided by this research are valuable to researchers and practitioners in making informed decisions, considering factors such as compression ratio, image quality, and computational complexity. In conclusion, this research contributes to the advancement of image compression techniques, enabling accurate and efficient handling of digital images in a wide range of applications.

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