An Overview of Lossless Digital Image Compression Techniques

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Abstract

Lossless compression is necessary for many high performance applications such as geophysics, telemetry, non-destructive evaluation, and medical imaging, which require exact recoveries of original images. Lossless image compression can be always modeled as a two-stage procedure: decorrelation and entropy coding. The first stage removes spatial redundancy or inter-pixel redundancy by means of run-length coding, SCAN language based methodology, predictive techniques, transform techniques, and other types of decorrelation techniques. The second stage, which includes Huffman coding, arithmetic coding, and LZW, removes coding redundancy. Nowadays, the performances of entropy coding techniques are very close to its theoretical bound, and thus more research activities concentrate on decorrelation stage. JPEG-LS and JPEG-2000 are the latest ISO/ITU standards for compressing continuous-tone images. JPEG-LS is based on LOCO-I algorithm, which was chosen to incorporate the standard due to its good balance between complexity and efficiency. Another technique proposed for JPEG-LS was CALIC. JPEG-2000 was designed with the main objective of providing efficient compression for a wide range of compression ratios.

Keywords

Lossless Compression, Image Coding, Entropy Coding, Decorrelation, Coding Standards.

INTRODUCTION

Digital images commonly contain lots of redundant information, and thus they are usually compressed to remove redundancy and minimize the storage space or transport bandwidth. If the process of redundancy removing is reversible, i.e. the exact reconstruction of the original image can be achieved, it is called lossless image compression; otherwise, it is called lossy image compression. Scientific or legal considerations make lossy compression unacceptable for many high performance applications such as geophysics, telemetry, non-destructive evaluation, and medical imaging, which will still require lossless image compression. The techniques employed in lossless image compression are all fundamentally rooted in entropy coding theory and Shannon's noiseless coding theorem, which guarantees that as long as the average number of bits per source symbol at the output of the encoder exceeds the entropy (i.e. average information per symbol) of the data source by an arbitrarily small amount, the data can be decoded without error. This paper reviews various lossless image compression methodologies and the state-of-the-art lossless image coding standards. Lossless image compression can be always modeled as a two-stage procedure: decorrelation and entropy coding. The first stage removes spatial redundancy or inter-pixel redundancy by means of run-length coding, SCAN language based methodology, predictive techniques, transform techniques, and other types of decorrelation techniques. The second stage, which includes Huffman coding, arithmetic coding, and LZW (LZW also removes spatial redundancy), removes coding redundancy. The problem with current entropy coding algorithms is that the alphabets tend to be large and thus lead to computationally demanding implementations. A general solution to this problem is to define several very simple coders that are nearly optimal over a narrow range of sources and adapt the choices of coder to the statistics of input data. Nowadays, the performances of entropy coding techniques are very close to its theoretical bound, and thus more research activities concentrate on decorrelation stage. Current standards for lossless compression include: Lossless JPEG, JBIG, GIF, Photo CD, PNG, etc. JPEG-LS and JPEG-2000 are the latest ISO/ITU standards for compressing continuous-tone images.

DECORRELATION TECHNIQUES

Correlation between samples, which is present in nearly all kinds of signals, represents redundant information that need not be transmitted if reversible decorrelation techniques are applied. Decorrelation, also known as "whitening", can be accomplished by many techniques.

Predictive Techniques

Linear prediction is an effective decorrelation technique that can be completely reversible. In the lossless coding literature, linear prediction is frequently referred to as differential pulse code modulation (DPCM). For each sample, a prediction of its value is formed from a weighted sum of neighboring samples. The difference data, or prediction residual, generally has much lower entropy than the original data. The predictor weights, or coefficients, may be fixed or adaptive.

Transform Technique

Transform techniques are frequently employed in lossy compression systems because they excel decorrelation. However, most transforms, such as DCT and DFT, are difficult to be applied in lossless signal coding because their transform coefficients are real-valued or complex-valued and must be quantized for coding. One transform technique that may be directly applied to lossless signal coding is the discrete Walsh-Hadamard transform (WHT). Since the coefficients of the WHT are binary fractions, quantization is not necessary.

Multi-resolution Techniques

A number of multi-resolution techniques including hierarchical interpolation (HINT), Laplacian pyramid, and S-transform have been successfully employed in the decorrelation of image data. These methods all form a hierarchy of data sets which represent the original data with varying resolutions. Therefore, these techniques also support progressive transmission which allows data to be decoded in several stages in increasing resolutions. The basic process of these multi-resolution techniques is to keep sampling the original data and entropy-code the sub-sample until all intermediate samples have been estimated and sampled.

ENTROPY CODING

Once the data has been decorrelated, more compression can be achieved by applying entropy coding as long as the probability mass function (PMF) of the resulting samples is not uniform. The fundamental concept in entropy coding is to assign the shortest codewords to the symbols that appear most often, and the longest to those appear infrequently. The average bitrate can be made to approach the entropy of the decorrelated data. Most signal compression schemes employ Huffman coding or Arithmetic coding. In addition, several compression schemes use sub-optimal variable length coders that are specifically designed for speed or ease of implementation.

Huffman Coder

Huffman coder always assigns long codewords to less-frequent symbols and short codewords to frequent symbols. Huffman codes are optimal in the sense that they generate a set of variable length binary codewords of minimum average length, as long as the source alphabet and PMF are available. Huffman codes always produce an average code length within one bit of the entropy bound. Most practical Huffman coders are adaptive and estimate the source PMF from the coded samples.

Arithmetic Coding

In arithmetic coding, codewords are constructed by partitioning the range of numbers between zero and one. As each symbol is encoded, the range is decreased by the amount inversely proportional to the probability occurrence of the symbol. When the range is sufficiently narrow, the partitioning is terminated and the codeword is assigned a binary fraction which lies within the final range.

LZW Coder

Lempel-Ziv-Welch (LZW) coder, which was originally developed for text compression, has also been applied to signal compression. LZW is actually a dictionary-based technique. When a sequence of symbols matches a sequence stored in the dictionary, an index is sent rather than the symbol sequence itself. If no match is found, the sequence of symbols is sent without being coded and the dictionary is updated.

Alternative Approaches

A significant difficulty in employing the above techniques is that alphabets for signal compression tend to be large, leading to implementations that require massive computational resources. To solve this problem, a couple of approaches have been developed. Usually coupled with a simple DPCM predictor, the Rice coder consists of several very simple coders which are nearly optimal over a very narrow range of source entropies. The system adapts to the input data by estimating the source entropy and selecting the appropriate coder. Another solution is to define a number of contexts based on the characteristics of samples being coded. The context is then used to select a coder from several smaller ones.

ALGORITHM REVIEW

Lossless Compression Standard

Modern lossless image compression, which is based on the modeling/coding paradigm, can be traced back to the Sunset algorithm in the early 1980s. In 1986, a collaboration of three major international standards organizations (ISO, CCITT, and IEC) lead to the creation of a committee known as Joint Picture Experts Group (JPEG). The charter of JPEG is to develop an international standard for compression and decompression of continuous-tone, still frame, color images. The resulted JPEG standard includes four basic compression methods: three of them are based on DCT and are used for lossy compression; the fourth one, known as lossless JPEG, is used for lossless compression. In lossless JPEG, two different schemes are specified: one is using arithmetic coding, and the other one is using Huffman coding. Even though the compression gap between the Huffman coding and the arithmetic coding versions is significant, the latter did not achieve widespread usage due to its higher computational complexity requirements and to intellectual property issue. The latest lossless compression standard is JPEG-LS. The main goal of JPEG-LS is to provide efficient lossless compression at a reasonable complexity. JPEG-LS is based on LOCO-I (Low Complexity Lossless Compression for Image) algorithm, which was chosen to incorporate the standard due to its good balance between complexity and efficiency. Another technique proposed for JPEG-LS was CALIC (Context-based, Adaptive, Lossless Image Codec). JPEG-2000 was designed with the main objective of providing efficient compression for a wide range of compression ratios. The reversible discrete wavelet transform that JPEG-2000 uses for lossless compression provides a considerable improvement over the prediction-based lossless mode of JPEG.

LOCO-I Algorithm

LOCO-I (LOw COmplexity LOssless COmpression for Image), proposed by Weinberger, Seroussi, and Sapiro, is the algorithm at the core of the new ISO/ITU standard for lossless compression of continuous-tone images - JPEG-LS. It is conceived as a "low complexity projection" of the universal context modeling paradigm. It is based on a fixed context model, which approaches the capability of the more complex universal techniques for capturing high-order dependencies. LOCO-I attains compression ratios similar or superior to those obtained with the state-of-the-art schemes based on arithmetic coding at a much lower complexity level.

LOCO-A Algorithm

LOCO-A, specified as an extension of the baseline JPEG-LS standard, is an arithmetic coding version of LOCO-I. This extension addresses the basic limitations that the standard presents when dealing with very compressible images, or images that are far from satisfying the assumptions underlying the model in JPEG-LS. LOCO-A closes most of the compression gap between JPEG-LS and CALIC at the price of the additional computational complexity introduced by the arithmetic coder. The basic idea behind LOCO-A is to cluster contexts with similar conditional distributions into conditioning states.

CALIC Algorithm

CALIC (Context-based, Adaptive, Lossless Image Codec) coder, proposed by Wu and Memon, obtains higher lossless compression ratios for continuous-tone image than other lossless techniques with relatively lower time and space complexities. CALIC puts heavy emphasis on image data modeling. A unique feature of CALIC is the use of a large number of modeling contexts to condition a nonlinear predictor and adapt the predictor to varying source statistics. The low time and space complexities are also attributed to efficient techniques for forming and quantizing modeling contexts. CALIC is a sequential coding scheme that encodes and decodes in raster scan order with a single pass through the image. CALIC operates in two modes: binary and continuous-tone. Although conceptually more elaborate than many existing lossless image coders, CALIC is computationally simple, involving mostly integer arithmetic and simple logic. Both the encoding and decoding algorithm are suitable for parallel and pipelined hardware implementation while supporting sequential buildup.

SCAN-based Algorithm

Bourbakis and his team have proposed a hybrid system for real-time lossless image compression and a context-based lossless image compression scheme, both of which are based on SCAN language. SCAN is a special purpose context-free language that describes and generates a wide range of array accessing algorithms from a set of simple ones. These algorithms represent scan techniques for image processing, but at the same time they stand as generic data accessing strategies. SCAN language is actually a bit-plane based methodology, which focuses on the spatial redundancy that exists between neighboring pixels. Incorporated with DPCM, run-length encoding, and Huffman coding, the system has consistently achieved compressions of 5.3bits/pixel to less than 4.0bits/pixel with the test image 'Lena'.

Prediction-based Algorithm

A large part of the research activity has focused on a specific type of compression technique, loosely referred to as lossless DPCM or lossless predictive coding. If the prediction of the predictor is reasonably accurate, then the distribution of prediction error is concentrated near zero and has significantly lower zero-order entropy compared to the original image. The current JPEG standard uses a predictive scheme in its lossless mode. It provides eight different predictors for selection.

In response to the call for proposals for a new lossless image compression standard, nine proposals have been submitted to ISO. From the first round evaluation, it is clear that transform-coding based proposals do not provide as good compression ratios as algorithms proposed based on predictive techniques. There are three prevalently proposed predictors: MED, GAP, and ALCM.

Other Algorithms

FELICS (Fast, Efficient Lossless Image Compression System) algorithm can be considered a first step in bridging the compression gap between simplicity-driven schemes and the schemes based on context modeling and arithmetic coding. CREW (Compression with Reversible Embedded Wavelets) uses an integer-to-integer wavelet transform and thus allows embedded coding. The novelty of the rich set of features provided by CREW triggered a new ISO standardization effort, JPEG2000. Ranganathan, Romaniuk, and Namuduri proposed a lossless image compression algorithm using variable block size segmentation, which eliminates local redundancy by representing the neighborhood in a compact form and eliminates global redundancy by encoding the repeated patterns. Embedded Image-Domain Adaptive Compression technique (EIDAC) is based on a context-adaptive bit-plane coder, where each bit-plane is encoded with a binary arithmetic encoder. Li and Lei proposed a new algorithm for lossless compression of computer-generated compound image. The algorithm consists of two parts: intra-plane coding and inter-plane coding. The coder is working in three different modes to match the local statistics of the image source. Said and Pearlman proposed a new multi-resolution image transform called S+P-transform that is suited for both lossless and lossy compression. The new transformation is similar to sub-band decomposition, but can be computed with only integer addition and bit-shift operations. Dewitte and Cornelis proposed a lossless integer wavelet transform. The new integer wavelet transform allows implementation of multi-resolution subband compression schemes, in which the decompressed data are gradually refined, retaining the option of perfect reconstruction.

COMPARATIVE EVALUATION

In this section we provide a comparative table to evaluate the performance of the lossless compression schemes.

Table-1: Comparative Results of "Lena" on Selected Image Comparison Approaches

Approach	Compression Ratio	Comments
DPCM	1.66:1	Header data not included in compression calculation. Huffman code uniquely generated for each image.
Pyramid Coding	1.73:1	Header data not included in compression calculation. Huffman code uniquely generated for each image. Approach supports progressive transmission.
Bit Plane	1.65:1	DPCM gray scale pre-processing followed by bit-plane processing
Adaptive Quadtree Segmentation	1.81:1	Exploits both local and global redundancies. Header data included in compression calculation.
S+P Transform	1.92:1	Approach supports progressive transmission.
Universal Context Modeling	1.93:1	Context algorithm with binary tree and conditional autoregressive prediction.
SCAN Bit-plane	1.72:1	
JPEG-2000	1.91:1	
SCAN-Context	1.91:1	

CONCLUSION

Comparing the performance of compression technique is difficult unless identical data sets and performance measures are used. Some techniques perform well for certain classes of data and poorly for others. Nowadays, since practical adaptive entropy coders are nearly optimal, future research in lossless signal coding is expected to concentrate on the decorrelation stage. Significant improvements are likely to require much more complex and computationally demanding source models.

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