3D SCALABLE LOSSLESS COMPRESSION OF MEDICAL IMAGES BASED ON GLOBAL AND LOCAL SYMMETRIES

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ABSTRACT

We recently proposed a symmetry-based scalable lossless compression method for 3D medical images using the 2D integer wavelet transform and the embedded block coder with optimized truncation (EBCOT). In this paper, we present two major contributions that enhance our early work: 1) a new block-based intra-band prediction method that exploits the global and local symmetries of the wavelet-transform sub-bands based on the main axis of symmetry as detected using the analytical Fourier-Mellin transform; and 2) a new inter-slice DPCM prediction method that exploits the correlation between slices. Performance evaluations on real 3D medical images show an average improvement of up to 17% in lossless compression ratios when compared to the state-of-the-art compression methods including 3D-JPEG2000, JPEG2000 and H.264 intra-coding.

Index Terms— scalable lossless compression, 3D medical images, EBCOT, symmetry, wavelet transform, JPEG2000, H.264.

1. INTRODUCTION

Over the past decade, three dimensional (3D) medical imaging has become a main pillar of clinical research and practice, making this type of image data an integral part of any patient's records. These routinely acquired 3D medical images, e.g., magnetic resonance imaging (MRI) and computed tomography (CT), comprise two dimensional (2D) images (or slices) of cross-sections of the anatomy of a region of interest (ROI) and are usually very large in file size.

The increasingly sophisticated data archiving and networking technologies render it crucial to improve techniques that would enable efficient storage and quick access to 3D medical images for future study and follow-up. Lossless compression methods are usually employed to reduce the storage burden of such data while avoiding any loss of valuable clinical information. Although most of the lossless compression methods for 3D medical images reported in the literature attain a good lossless compression performance [1-4], they do not fully exploit some of the inherent characteristics of 3D medical images, such as the global and local symmetries of the slices, thus leaving room for improvement.

In this paper, we extend our previous work in [4] and propose a novel scalable lossless compression method for 3D medical images. The proposed method employs the 2D integer wavelet transform (2D-IWT) to decompose slices into sub-bands, a new block-based intra-band prediction method to reduce the energy of the sub-bands by exploiting the global and local symmetries, a new inter-slice differential pulse code modulation (DPCM) prediction method to exploit the correlation between slices, and the embedded block coder with optimized truncation (EBCOT) to compress the final residual data [5]. The new intra-band prediction method predicts the value of coefficients on a block-by-block basis by exploiting the global and local symmetries of the sub-bands based on the main axis of symmetry as detected using the Fourier-Mellin transform [6]. The new inter-slice DPCM prediction method exploits the correlation between slices by calculating the difference between samples of adjacent slices.

We validate the compression efficiency of our proposed method on real MRI and CT volumes and show important gains in lossless compression ratios compared to current state-of-the-art compression methods including 3D-JPEG2000, JPEG2000 and H.264 intra-coding.

2. PROPOSED 3D COMPRESSION METHOD

The block diagram of the proposed compression method is illustrated in Fig. 1. Given a 3D medical image, each slice is first decomposed using the 2D-IWT with n levels of decomposition. This transformation maps integers to integers and allows for perfect invertibility with finite precision arithmetic, which is required for perfect reconstruction of a signal [7]. Each resultant sub-band is coded independently using a block-based intra-band prediction method that exploits the global and local symmetries. The associated residual sub-bands are then coded using inter-slice DPCM prediction to exploit the correlation between slices. The final residual data are entropy coded into l quality layers using EBCOT to generate a bit-stream that is both resolution and quality scalable [5]. All prediction parameters are compressed using a variable length coder (VLC) and are included as a main header in the compressed bit-stream.

The following sections detail the block-based intra-band and inter-slice DPCM prediction methods.

2.1. Block-based intra-band prediction method

Due to the inherent symmetry of the human anatomy, cross-sections of the ROIs depicted in slices of 3D medical images are typically symmetrical. This symmetry is preserved as global and local symmetries in the location and value of wavelet coefficients of the 2D-IWT sub-bands.

Global symmetry refers to the symmetry of the whole sub-band as defined by a main axis of symmetry, while local symmetry refers to the symmetry of a small region within the sub-band as defined by a local axis of symmetry (see Fig. 2).

In our intra-band prediction method, we exploit the global and local symmetries to predict the value of coefficients and reduce the overall energy of the sub-bands. To achieve this, we first identify the global symmetry of the sub-bands by employing the analytical

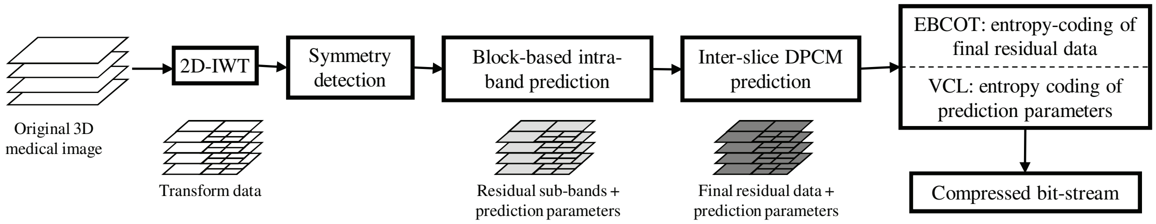


Fig. 1. Block diagram of the proposed scalable lossless compression technique. 2D-IWT: two-dimensional integer wavelet transform. DPCM: differential pulse code modulation. EBCOT: embedded block coder with optimized truncation. VCL: variable length coding.

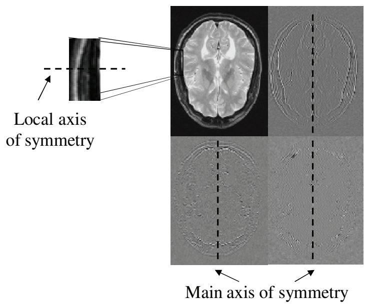
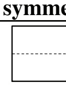
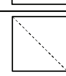
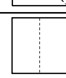
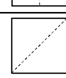


Fig. 2. Example 2D-IWT sub-bands for one level of decomposition of an axial view slice of a brain MRI scan. Note the global and local symmetries of the sub-bands.

Fourier-Mellin transform [6]. This transform is used to evaluate motion parameters between gray-level objects having the same shape with distinct scale and orientation, which in turn may be used to detect the angle of the main axis of symmetry of gray-level images as measured clock-wise from the *x*-axis [6].

In this work, a sub-band is modeled to have one of four types of global symmetry according to the value of the measured angle as summarized in Table 1.

Table 1. Types of global symmetry of sub-bands

Angle of main axis of symmetry (deg)*	Type of global symmetry	
[0º, 23º) [158º, 180º]	Horizontal	
[23º, 68º)	Diagonal-down	
[68º, 113º)	Vertical	
[113º, 158º)	Diagonal-up	

* measured clock-wise from the *x*-axis.

We partition each sub-band into two areas of equal size, *A* and *B,* along the main axis of symmetry. We divide areas *A* and *B* into blocks of 16×16 coefficients and we process the blocks in an alternating fashion, such that after processing a block in *A*, we process the block located in the corresponding symmetrical position in *B* as defined by the main axis of symmetry (see Fig. 3).

We predict each block using any previously coded block after undergoing a spatial transformation. We employ eight spatial transformations that modify the spatial relationship between coefficients in a block, mapping coefficient locations in an input

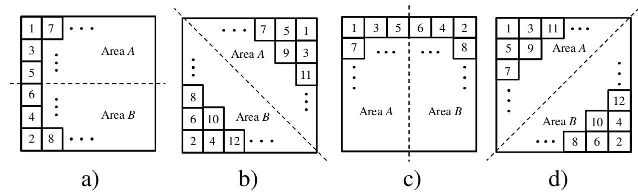
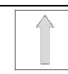
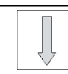
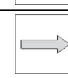
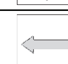
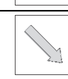
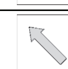
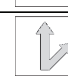
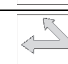
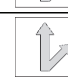
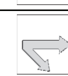
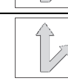
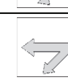
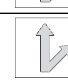
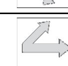
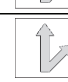
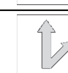


Fig. 3. Partitioning of a sub-band into areas *A* and *B* and processing order of blocks according to the global symmetry: a) horizontal, b) diagonal-down, c) vertical, and d) diagonal-up

block to new locations in an output block, as summarized in Table 2 [4]. We further divide blocks into smaller sub-blocks of 8×8 and 4×4 coefficients if that improves the compression performance.

Table 2. Spatial transformations

Geometric operation	Sample input block	Output block
1. Vertical flip		
2. Horizontal flip		
3. Diagonal flip		
4. Left rotation(90°)		
5. Right rotation(90°)		
6. Left rotation(90°) + vertical flip		
7. Right rotation(90°) + vertical flip		
8. No operation		

We calculate the difference between the current block and the predicted block (i.e., we compute the residual block) and select the spatial transformation that generates the residual block with the lowest energy content. If no spatial transformation generates a residual block with less energy than the original block, we employ no prediction for that particular block. After processing all blocks, we re-organize the generated residual data into sub-bands.

The advantages of our new intra-band prediction method are twofold. First, we exploit any local symmetries by employing small blocks and by allowing the coder to use any previously coded block for prediction; and second, we exploit the global symmetry by processing blocks in a specific order, so to allow the coder to predict a block using the corresponding symmetrical block as defined by a main axis of symmetry.

2.2. Inter-slice DPCM prediction method

After reducing the energy content of the sub-bands, we employ DPCM prediction to exploit the correlation between the residual sub-bands in adjacent slices. DPCM prediction algorithms calculate the difference between adjacent samples and generate residual data. In this work, we employ inter-slice DPCM prediction on groups of 16×16×s samples (see Fig. 4(a)), which we code independently so to allow fast decoding to different sub-bands and slices of the 3D data.

As mentioned earlier, slices of 3D medical images depict the cross-sections of the anatomy of an ROI and are usually highly correlated. Empirical evidence suggests that sample p in slice k may be highly correlated to any of its nine immediate neighbors in slice $k-1$ or slice $k+1$, as illustrated in Fig. 4(b). We propose to employ five prediction modes to exploit these correlations by calculating the difference, in one of five different directions, between samples of residual sub-bands in adjacent slices, as illustrated in Fig. 5.

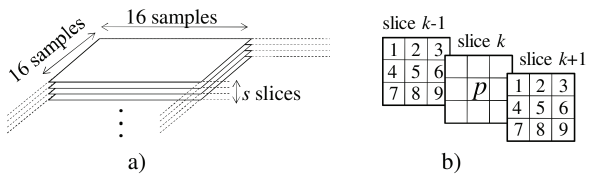


Fig. 4. a) Group of 16×16×s samples used in inter-slice DPCM prediction. b) Sample p in slice k and its nine immediate neighbors in slice $k-1$ and slice $k+1$.

We select the prediction mode that generates the residual group of samples with the lowest energy content. If no prediction mode generates a residual group of samples with less energy than the original group, we employ no DPCM prediction for that particular group. After processing all groups of samples, we re-organize the generated final residual data into slices and compress each into l quality layers using EBCOT [5].

We compress all prediction parameters generated by the intra-band and inter-slice DPCM prediction methods (i.e., size of blocks, spatial transformation and prediction modes) using a VLC with a single infinite-extent codeword table generated using an Exp-Golomb code of order zero [8].

3. PERFORMANCE EVALUATION

We tested the performance of our compression method on four MRI and three CT volumes (see Table 3, column1). Volumes 1 and 2 comprise MRI slices (axial view) of a human head; volume 3 comprises MRI slices (sagittal view) of a human knee; volume 4 comprises MRI slices (coronal view) of a human head; and volumes 5-7 comprise consecutive slices (axial view) of the Visible Human Project data set maintained by the National Library of Medicine (*http://www.nlm.nih.gov*).

For comparison purposes, Table 3 tabulates the lossless compression ratios and bit-rates (in bits per pixel) of five

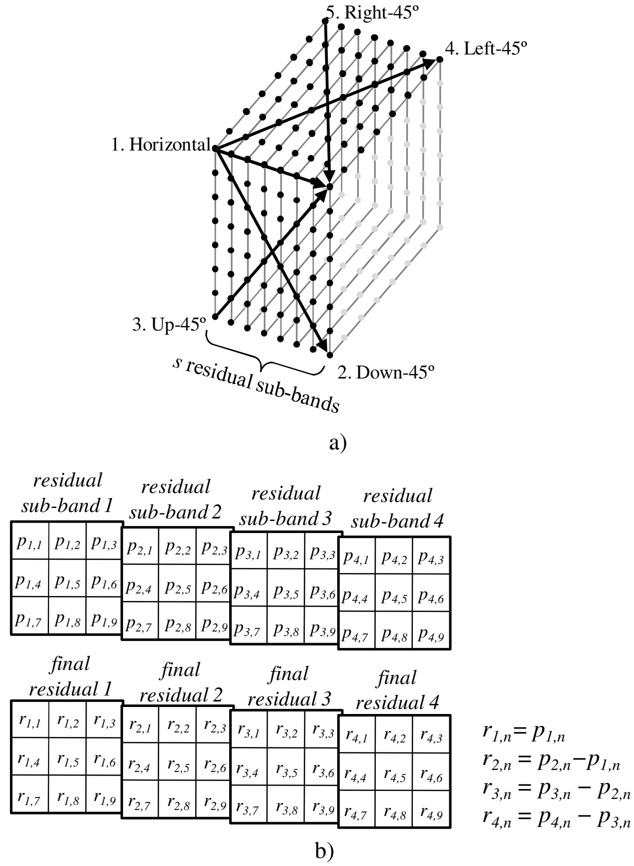


Fig. 5. a) The five proposed prediction modes for inter-slice DPCM prediction: 1. Horizontal, 2. Down-45º, 3. Up-45º, 4. Left-45º and 5. Right-45º. b) Calculation of the final residual data for a group of 3×3×4 samples using the *horizontal* prediction mode. $p_{s,n}$ denotes the nth sample of residual sub-band s; and $r_{s,n}$ denotes the nth final residual sample of sub-band s.

compression methods: JPEG2000, 3DJPEG2000, H.264 intra-coding, the symmetry-based method in [4] and our proposed compression method. JPEG2000 and 3D-JPEG2000 [9] are wavelet-based scalable compression methods, while H.264 intra-coding is a video-compression standard that employs selectable position-dependent linear combinations of neighboring sample values to form prediction blocks [10].

In our proposed compression method, we decomposed each slice using four levels of decomposition. We employed blocks of 16×16, 8×8 and 4×4 coefficients for intra-band prediction (with the block size and spatial transformation being selected by the encoder). We employed groups of 16×16×16 samples for inter-slice DPCM prediction of the residual sub-bands (with the prediction mode being selected by the encoder). We entropy coded the final residuals using EBCOT with code-blocks of 32×32 samples to create a layered bit-stream. For the case of the symmetry-based method in [4], we also created a layered bit-stream and employed four levels of decomposition and blocks of 16×16, 8×8 and 4×4 coefficients. For the case of JPEG2000 and 3D-JPEG2000, we employed the same compression parameters as in [4]: a layered bit-stream with four levels of decomposition, code-blocks and precincts of 32×32 coefficients to group coefficients describing the same spatial region at the same

Table 3. Lossless compression ratios and bit-rates of 3D medical images using various compression methods

Modality *(slices: pixels per slice: bits per pixel)*	**Compression method**				
	H.264 intra-coding	JPEG2000	3D-JPEG2000	Symmetry-based [4]	**Proposed method**
	compression ratio (bit-rate: bits per pixel)				
1. MRI *(24:192×256:16)*	2.65:1 (6.03 bpp)	2.62:1 (6.10 bpp)	2.71:1 (5.90 bpp)	3.25:1 (4.92 bpp)	**3.29:1 (4.86 bpp)**
2. MRI *(35:256×256:16)*	2.41:1 (6.63 bpp)	2.57:1 (6.22 bpp)	2.68:1 (5.97 bpp)	3.29:1 (4.86 bpp)	**3.33:1 (4.80 bpp)**
3. MRI *(50:512×512:8)*	2.93:1 (2.73 bpp)	2.91:1 (2.74 bpp)	2.96:1 (2.70 bpp)	3.18:1 (2.51 bpp)	**3.19:1 (2.49 bpp)**
4. MRI *(180:176×176:16)*	3.27:1 (4.89 bpp)	3.37:1 (4.74 bpp)	3.58:1 (4.46 bpp)	3.70:1 (4.32 bpp)	**3.73:1 (4.28 bpp)**
5. CT *(40:512×512:16)*	3.89:1 (4.11 bpp)	4.44:1 (3.60 bpp)	4.51:1 (3.54 bpp)	5.34:1 (2.99 bpp)	**5.38:1 (2.97 bpp)**
6. CT *(40:512×512:16)*	3.81:1 (4.19 bpp)	4.39:1 (3.64 bpp)	4.49:1 (3.56 bpp)	5.28:1 (3.03 bpp)	**5.32:1 (3.00 bpp)**
7. CT *(40:512×512:16)*	3.52:1 (4.92 bpp)	4.16:1 (3.84 bpp)	4.28:1 (3.73 bpp)	4.50:1 (3.55 bpp)	**4.54:1 (3.52 bpp)**

MRI: magnetic resonance imaging. CT: computed tomography

decomposition level. For the case of H.264 intra-coding, we employed blocks of 16×16, 8×8 and 4×4 pixels (with the block size and prediction method being selected by the encoder) and no quantization for the residual data.

Results reported in Table 3 show that for all 3D test images, our method achieves the highest lossless compression ratios with an average improvement of 17% over JPEG2000 and H.264 intra-coding, of 15% over 3D-JPEG2000, and of 1% over the symmetry-based method in [4]. Even though JPEG2000 and 3D-JPEG2000 also employ a 2D-IWT to decompose the slices into sub-bands, the high number of edges usually found in 3D medical images results in high-energy sub-bands, which consequently affects the compression performance of the entropy coder. H.264 intra-coding only employs the neighboring sample values for prediction of a block of pixels. This performs well in smooth images with only a small number of edges, which is not the case for most 3D medical images.

It is important to mention that for images with mainly a global symmetry (i.e., axial and coronal view) and for those with mainly local symmetries (i.e., sagittal view), our proposed method achieves higher lossless compression ratios than those achieved by the symmetry-based method in [4]. Let us remember that the new block-based intra-band prediction method is designed to reduce the energy of the sub-bands by exploiting both, global and local symmetries. Moreover, the new inter-slice DPCM prediction method further reduces the energy of the sub-bands by exploiting the correlation between slices. The final result is sub-bands with low energy content, which are efficiently compressed by EBCOT.

4. CONCLUSIONS

We proposed a 3D scalable lossless compression method for medical image data based on global and local symmetries. The proposed method, which improves on our early work on symmetry-based medical image compression, employs the 2D integer wavelet transform to decorrelate the data, a new block-based intra-band prediction method to reduce the energy of the sub-bands by exploiting the global and local symmetries, a new inter-slice DPCM prediction method to exploit the correlation between slices, and EBCOT to compress the final residual data and achieve resolution and quality scalability. Performance evaluations showed an average improvement in lossless compression ratio of 17% over JPEG2000 and H.264 intra-coding, and of 15% over 3D-JPEG2000, which validates the compression efficiency of the proposed method.

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