THREE-DIMENSIONAL WAVELET CODING OF MAGNETIC RESONANCE IMAGES

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Abstract— **Three-dimensional significance-linked connected component analysis (3D-SLCCA) is proposed for compression of volumetric magnetic resonance imaging (MRI) data. Due to relatively low inter-slice correlation and high noise level of MRI, 3D-SLCCA treats two MRI slices as a processing unit. By using the Haar wavelet, the temporal lowpass and temporal highpass subbands are obtained as the sum and difference of two consecutive slices, respectively. Then dyadic spatial wavelet decomposition is applied on each temporal subband separately, and significant wavelet coefficients are organized and represented by using the SLCCA technique. The proposed 3D-SLCCA codec provides high compression efficiency, progressive volume representation, low complexity, and transmission error resilience. These desirable features make 3D-SLCCA especially well suited for use within a clinical picture archiving and communication system (PACS) and telemedicine.**

Keywords— **Volumetric data compression, wavelet coding, data organization and representation, significance-linked connected component analysis, video coding**

I. INTRODUCTION

An increasing volume of medical imagery is being created, stored, communicated, and evaluated exclusively in digital form with advances in digital capture devices, computers, and network infrastructure. The extensive and inexpensive availability of digital medical imaging technologies is one of the major factors increasing the popularity of the clinical picture archiving and communication system (PACS) [1] and telemedicine. An average hospital, however, may generate terabytes of medical imaging patient data annually, which necessitates medical data compression for storage and communication. *Lossless* methods, although widely used in clinical practice, provides only minimal compression usually not more than a factor of two to three. Application of *lossy* techniques is gaining acceptance in clinical medicine like radiology image compression provided that salient anatomical and physiological information is preserved. Lossy compression, however, may introduce picture degradation which has legal implications requiring careful study.

Highly efficient volumetric data compression can be achieved by exploiting both within-slice and inter-slice correlation. Although adjacent slices are anatomically correlated to each other, this correlation has been difficult to exploit. This triggered extensive research and development resulting in a large number of medical image compression algorithms [2]. Conceptually, there are three basic approaches proposed in the literature for volumetric medical data compression:

- slice-by-slice compression using still image coding techniques;
- applying video compression techniques by treating the third dimension as time;
- three dimensional compression, where the entire volume is treated as one processing unit.

In the paper, we propose to use three-dimensional significance-linked connected component analysis (3D-SLCCA) for volumetric magnetic resonance imaging (MRI) data compression. In 3D-SLCCA, two adjacent MRI slices are treated as a processing unit. By using the Haar wavelet, the temporal lowpass and temporal highpass subbands are obtained as the sum and difference of two consecutive slices, respectively. After dyadic spatial wavelet decomposition of each temporal subband, wavelet coefficients are quantized with a uniform quantizer. While the *within-subband* clustering property of wavelet-transformed slices is exploited by morphological conditioned dilation operation, the *cross-scale* dependency is exploited by using the significance link technique. Finally, the magnitude of significant wavelet coefficients are transmitted in bit-plane order by using adaptive arithmetic coding with our scale/space-variant high order Markov source modeling. In addition to high compression efficiency, the proposed 3D-SLCCA codec provides progressive volume representation, low complexity, and transmission error resilience, which are highly desirable in medical data storage and telemedicine systems.

The rest of the paper is organized as follows. Sec-

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tion II reviews image and video coding techniques and their application for medical image compression. Algorithms specifically developed for volumetric medical data compression are also presented. The proposed codec, 3D-SLCCA, is detailed in Section III. Performance evaluation is given in Section IV, and the last section concludes the paper.

II. RELATED WORK IN VOLUMETRIC MEDICAL DATA COMPRESSION

The application of innovative data organization and representation strategies is crucial for today's high performance wavelet image compression algorithms. There have been several such high performance image codec developed, namely, Shapiro's embedded zerotree wavelet (EZW) [3], Said and Pearlman's set partitioning in hierarchical trees (SPIHT) [4], Servetto *et al.*'s morphological representation of wavelet data (MRWD) [5], and Chai *et al.*'s significance-linked connected component analysis (SLCCA) [6], [7], [8], [9], [10], [11]. All these wavelet-based techniques significantly outperform the discrete cosine transform (DCT)-based still image compression standard JPEG [12]. Experimental evidence shows that of the above four high performance wavelet codecs, SLCCA provides the best compression performance.

A straightforward extension of the above described high performance image codecs for volumetric medical data compression is their *slice-by-slice* application. Slice-by-slice compression provides acceptable performance while avoiding the difficulty of modeling and exploiting anatomical inter-slice correlation structures. While it efficiently exploits the within-slice correlation, the inter-slice correlation is ignored so compression ratios can be expected to be lower.

Applying video compression techniques for volumetric medical data compression might seem a reasonable approach. Due to the extremely high bandwidth requirement of motion pictures, video compression techniques have been intensively studied in the past decade in both academia and industry. A large number of standards have been adopted such as MPEG-1, MPEG-2, MPEG-4, H.261, H.263, etc. All these algorithms are built on the *hybrid-DCT* structure, where the temporal redundancy is exploited by using time-domain block-based motion estimation and motion compensation, and the remaining spatial redundancy is exploited by using DCT. Previously mentioned high performance wavelet image codecs can be extended to hybrid-wavelet video compression methods by replacing the DCT with wavelet transform combined with advanced data organization and representation strategies. Several such algorithms have been published [13], [14], [15], [16] and results superior to the hybrid-DCT scheme were achieved. Although well suited for motion pictures, applying hybrid-DCT/wavelet techniques for volumetric medical data compression has not been successful [17], i.e., it provided inferior performance in comparison with slice-by-slice methods. The reason for low performance is recognized in that the translational block motion model is unable to capture the anatomic correlation of volumetric data. As a solution, Nosratinia *et al.* used affine transformation with control grid interpolation as a motion model [18]. This advanced motion model was able to capture the anatomic inter-slice correlation and promising results were reported. However, the two major problems with motion estimation and motion compensation techniques include undesirable blocking artifacts, that would adversely effect clinical use and the extremely high computational cost, which requires specialized hardware for real-time implementation.

Three-dimensional (3-D) compression is the third alternative for volumetric medical data compression. In these algorithms, the entire volume is treated as one processing unit. The 3-D DCT compression was proposed in [19], and the 3-D wavelet transform was used in [20]. In [20], no advanced data organization and representation strategies are employed, i.e., *all* wavelet coefficients are quantized and encoded by using runlength coding and Huffman coding, and thus only moderate compression is achieved. Luo and Chen extend the SPIHT image codec for volumetric medical data compression [21]. In their algorithm, 64 slices constitute a processing unit, which requires 32 Mbytes of storage for a 512×512 slice resolution. Furthermore, individual slice access is impossible.

III. 3D-SLCCA FOR VOLUMETRIC DATA COMPRESSION

The block diagram of the proposed 3D-SLCCA codec [22], [23] for volumetric medical data compression is shown in Fig. 1. In the proposed system, only two slices constitute a processing unit. After temporal decomposition, each temporal subband is processed independently.

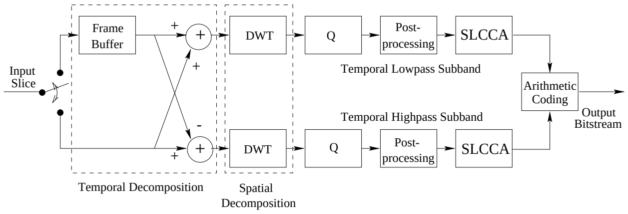


Fig. 1. Block diagram of 3D-SLCCA volumetric medical data compression technique.

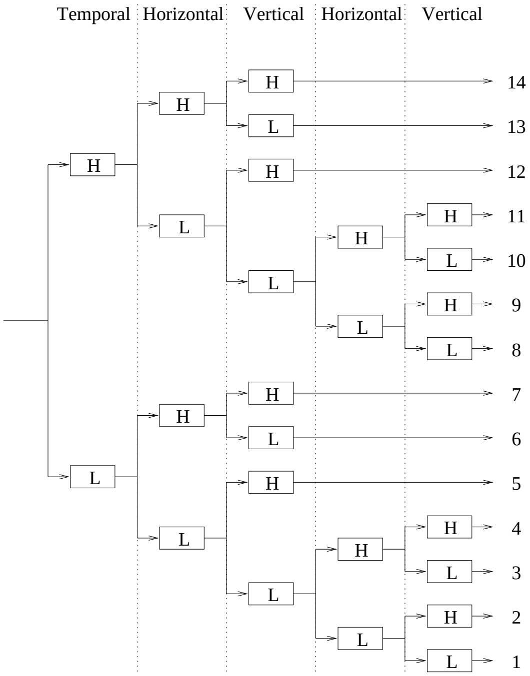
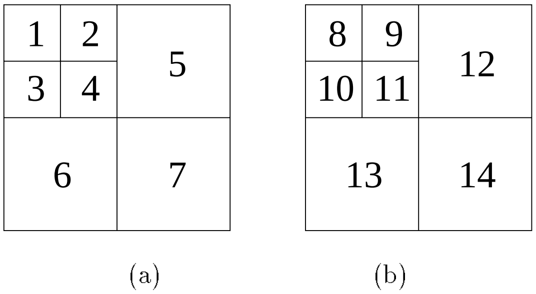


Fig. 2. 3-D wavelet decomposition structure applied in 3D-SLCCA.

A. *Three-Dimensional Wavelet Decomposition*

The applied wavelet decomposition structure is shown in Fig. 2, where the Haar wavelet, performed as the sum and difference of two consecutive slices, is used for temporal decomposition. Then, dyadic spatial wavelet decomposition is applied for each temporal subband separately by using Daubechies 9/7 biorthogonal wavelet filters. The resulting 14 spatio-temporal subbands by assuming two-scale spatial wavelet decomposition are illustrated in Fig. 3.



(a) (b)

Fig. 3. Illustration of two-scale spatial decomposition on two consecutive slices. (a) Temporal lowpass subband. (b) Temporal highpass subband.

In 3D-SLCCA, we propose to use dyadic spatial wavelet decomposition on both temporal subbands. As is evidenced by our experiments, applying dyadic wavelet decomposition on both temporal subbands not only slightly improves the performance, but also decreases the computational complexity. More importantly, after the spatial wavelet decomposition, the same processing is applied on both the temporal lowpass and temporal highpass subbands which largely reduces the implementation complexity.

B. *Significance-Linked Connected Component Analysis*

This section briefly reviews the SLCCA data organization and representation strategy. For more details, the readers are referred to [10].

The main components of the SLCCA technique include:

- exploitation of within-subband clustering by using conditioned dilation operation;
- exploitation of cross-scale dependency by using significance-linkage;
- adaptive arithmetic bit-plane encoding with scale/space-variant higher order Markov source modeling.

After spatial wavelet decomposition and scalar quantization, the so-called *significance map* is constructed. The significance map is a binary image of the same size as the original slice. Binary one means that the wavelet coefficient at the corresponding location is significant, and binary zero means that the wavelet coefficient at the corresponding location is insignificant. In SLCCA, the *within-subband* clustering property is exploited by morphological conditioned dilation [24] to recursively segment wavelet coefficients into clusters (connected components) of significant coefficients and thus to construct the significance map. As extremely small clusters likely do not produce discernible visual effects but render a higher boundary-to-area ratio, they are eliminated by using area thresholding to avoid the more expensive coding cost.

Naturally, the seed position of each connected component must be available at the decoder. In SLCCA, the *significance-linkage* technique is developed to predict the seed position of the child cluster from the position of the parent cluster. That is, two connected components or clusters are *significance-linked* if the significant parent belongs to one component, and at least one of its four children is significant and lies in another component. If the positioning information of the significant parent in the first component is available, the positioning information of the second component can be inferred through labeling the parent as having a significance-link. Since there are generally many significant coefficients in a connected component, the likelihood of finding significance-linkage between two connected components is fairly high. Apparently, labeling the significance-link costs much less than directly encoding the positioning information, and a significant saving on encoding cluster positions can be achieved.

The final component of the SLCCA algorithm is adaptive arithmetic coding based on our *scale/space-variant* high order Markov source modeling. After the encoding of the significance map, magnitudes of significant coefficients are encoded in bit-plane order. In global bit-plane order encoding, all the significant coefficients across all subbands in any given bit-plane are coded together, starting at the sign, and proceeding from the most significant bit-plane to the least significant bit-plane. The contexts or conditions used to define conditional probabilities at each pixel in each bit-plane are determined by the scale/space-variant significance status of its already transmitted eight spatial neighbors and its up-scaled parent as well.

C. Advantageous Properties of 3D-SLCCA

3D-SLCCA provides the following advantageous properties that are highly desirable in an effective and efficient medical data storage and communication system.

High compression efficiency: High compression efficiency is necessary in order to provide high picture quality at high compression ratios. Higher compression ratios mean that the same picture quality can be achieved using a smaller size or better picture quality can be provided with the same data size. As we will see in Section IV, 3D-SLCCA provides much higher compression efficiency when compared to slice-by-slice compression or motion compensated compression. High compression efficiency is of prime importance in telemedicine, where medical data needs to be transmitted over low bandwidth WAN.

Progressive volume representation: Progressive volume representation means that the same data can be accessed at different resolution and quality. It is an invaluable feature for browsing applications, when a physician can skim through a large number of coarsely decompressed images, and images only with interest are refined for further evaluation.

Low computational cost: Due to temporal filtering replaces computationally expensive motion estimation, 3D-SLCCA provides very low cost that enables real-time software-only implementation by using inexpensive desktop computers. Furthermore, only two slices are treated as a processing unit, which significantly reduces memory requirements in comparison with other proposed 3-D codecs.

Error resilience: Error resilience is important for transmission over telemedicine networks that may even incorporate unreliable wireless links. When compared to the hybrid-DCT/wavelet scheme, the undesirable error propagation is largely prevented in 3D-SLCCA, where two slices are coded as one unit, which prevents temporal error propagation, and there is no use of spatial prediction, which reduces spatial error propagation.

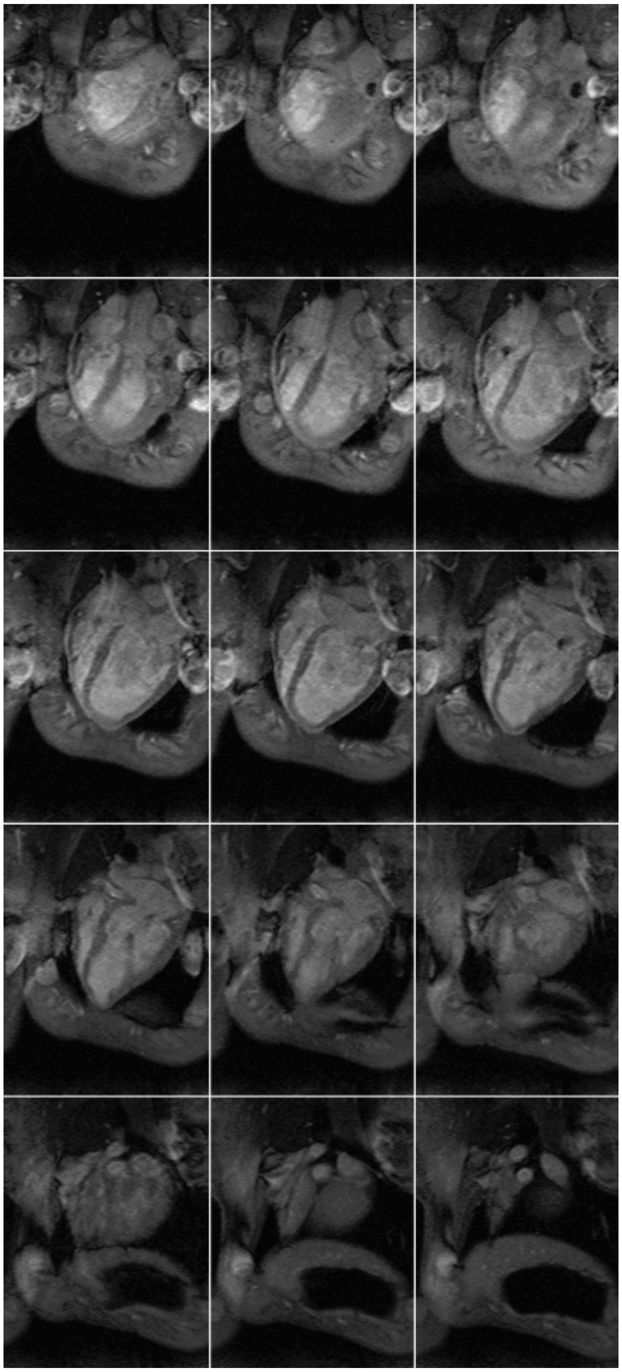


Fig. 4. Volumetric MRI data used in the experiments.

IV. PERFORMANCE EVALUATION

The data set used in the performance evaluation was obtained from the Magnetic Resonance Imaging

Laboratory at the Harvard Medical School. The volumetric data consists of 14 slices with each slice being of 512×384 pixels and 10 bits-per-pixel (bpp). Several slices of porcine cardiovascular MRI volumetric data is shown in Fig. 4. The low inter-slice correlation due to the few number of slices combined with image noise makes this data set especially challenging for compression.

The objective quality of the compression technique is measured by peak signal-to-noise ratio (PSNR) defined by

$$\mathrm{PSNR[dB]} = 20 \log_{10} \frac{1023}{\mathrm{RMSE}},$$

where RMSE is the root mean-squared error between the original and reconstructed slices. The compression ratio (CR) is calculated by

$$\mathrm{CR} = \frac{\text{Average size of the original slice}}{\text{Average size of the compressed slice}}.$$

In our experiments both PSNR and CR are computed from the actual decoded bitstream.

The evaluation of 3D-SLCCA, slice-by-slice SPIHT, and video significance-linked connected component analysis (VSLCCA) [16] is shown in Fig. 5 for the test data set at CR = 10:1. For natural motion pictures, VSLCCA is one of the best codecs published in the literature. However, for MRI data compression, 3D-SLCCA significantly outperforms VSLCCA by an average PSNR of 21.69 dB. The reasons for the poor performance of VSLCCA include not only the inefficient translational block motion model, but also the significant intensity variation among slices. 3D-SLCCA outperforms slice-by-slice SPIHT in PSNR by 1.26 dB on average.

The next set of experiments demonstrates the progressive transmission capability of 3D-SLCCA. Fig. 6 shows the original first slice, the decompressed slices with compression ratio ranging from CR = 10:1 to CR = 160:1, and the objective performance measured by PSNR. As seen, the decoded slice at CR = 160:1 is slightly smoothed, but no artifacts are introduced. Although this picture quality is not suitable for diagnosis, it is highly applicable for progressive browsing. Decoded slices up to CR = 40 show no visible distortion when compared to the original slice.

V. CONCLUSIONS

In this paper, a novel volumetric medical data compression technique called three-dimensional significance-linked connected component analysis was proposed. The scheme provides high compression efficiency, progressive volume representation, low computational cost, and error resilience. These properties make 3D-SLCCA suitable for MRI and other medical data storage and telemedicine systems. Further research directions include slice intensity equalization and extension of our 3D-SLCCA codec for time-varying volumetric medical data compression.

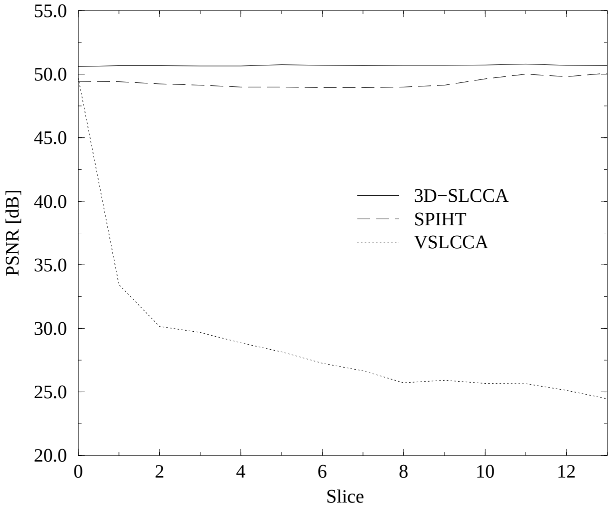


Fig. 5. Comparison of 3D-SLCCA, slice-by-slice SPIHT, and VSLCCA for volumetric MRI data compression of Fig. 4. Average PSNR is 50.70 dB, 49.34 dB, and 29.01 dB, for 3D-SLCCA, slice-by-slice SPIHT, and VSLCCA, respectively.

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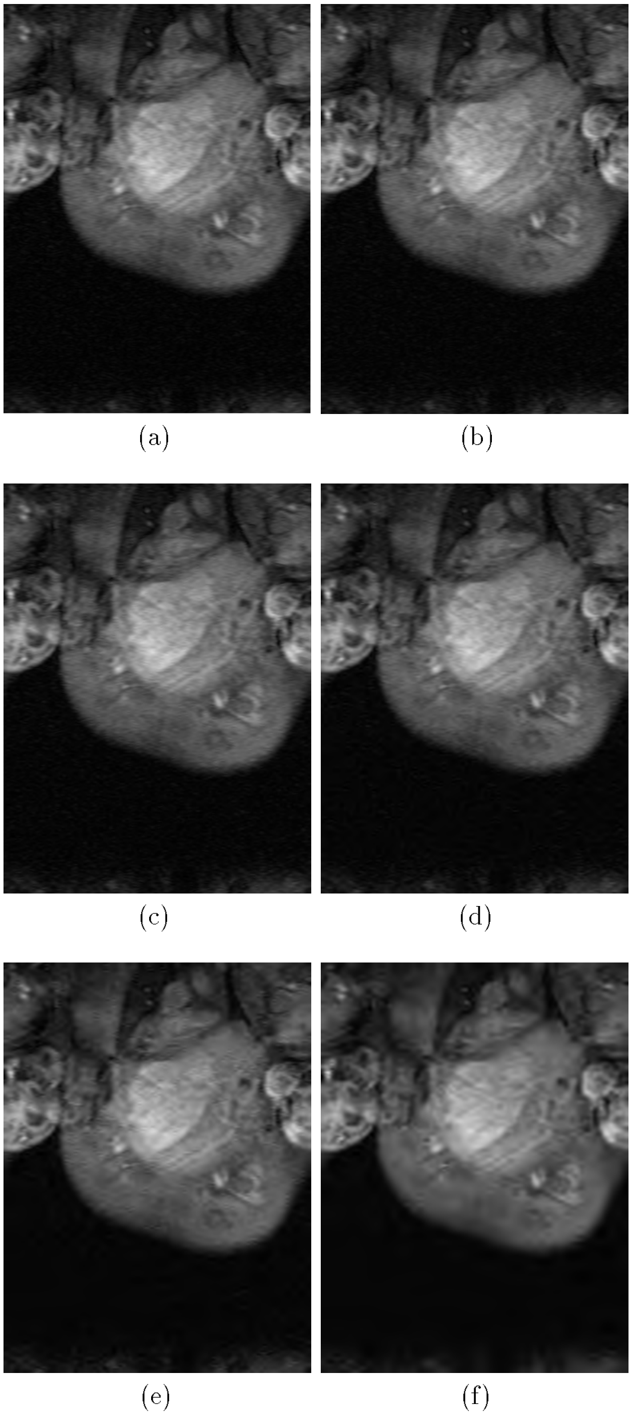

(a) (b)

(c) (d)

(e) (f)

CR	PSNR [dB]	Picture
10:1	50.61	(b)
20:1	44.35	(c)
40:1	40.81	(d)
80:1	37.80	(e)
160:1	35.47	(f)

Fig. 6. Progressive MRI data compression. (a) The original first slice. The reconstructed slices at CR = 10, 20, 40, 80, and 160 are shown in (b)–(f), respectively. The PSNR performance is given in the table.

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