A NOVEL PROGRESSIVE THICK SLAB PARADIGM FOR VOLUMETRIC MEDICAL IMAGE COMPRESSION AND NAVIGATION

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ABSTRACT

In this paper, we propose a novel thick slab paradigm which provides an efficient scheme to navigate through large three dimensional (3-D) medical data sets within the framework of wavelet based lossless volumetric compression. We also propose a 3-D wavelet-like multi-resolution decomposition to perform 3-D image compression, which provides better compression ratio and 3 times faster decoding than JPEG-2000 for large data sets of computed tomography modality, along with a clinical workflow for navigation application. The proposed method suits radiology applications better than JPEG-2000 as it improves the productivity of radiologists by reducing their waiting time while the data is being transferred from a remote database over the network, along with reduction in diagnosis time, by providing an efficient navigation scheme with high compression performance.

1. INTRODUCTION

Several of todays imaging techniques produce three dimensional (3-D) data sets. Medical imaging techniques, such as computed tomography (CT) and magnetic resonance (MR), generate multiple slices in a single examination, with each slice representing a different cross section of the body part being imaged. The growth in data volume directly translates to the need for compression schemes with high compression ratio so that the storage costs are kept at a minimum and speeding up of transmission across low bandwidth channels (e.g. for teleradiology applications) is achieved.

Apart from the need for better compression schemes, there is a great need for smart viewing of large 3-D data sets. Today, radiologists need to scan through 5 to 10 times more images at the same time to maintain their productivity. For modalities like CT and MR, the radiologists have to navigate through large data sets and provide their comments at desired locations, which requires an efficient data navigation scheme. Though, 3-D viewing is one natural choice to view the images, which promises speed up in viewing, radiologists are habituated to cine through two dimensional (2-D) images.

We propose a novel progressive thick slab paradigm which provides an efficient scheme to navigate through large 3-D medical data sets within the framework of wavelet based lossless volumetric compression while performing better than JPEG-2000 [1] in terms of compression ratio and decoding speed. The main motivation to propose this novel paradigm is to present a scheme which provides both high compression performance and efficient navigation capability, aiming to reduce the waiting time of radiologists while the data is being loaded from a remote database, along with their time for diagnosis, thus improving their productivity. Coding of 2-D images independently on a slice-by-slice basis of a 3-D volume using 2-D compression schemes do not exploit the dependencies that exist among pixel values in all three dimensions. Because pixels are correlated in all three dimensions, we investigated lossless 3-D compression of medical volumes, which is preferred over lossy compression schemes in medical applications. Within the framework of 3-D lossless compression, the primary idea of our proposed navigation method is to present the radiologists with representative slices/thick slabs (low resolution data along axial direction) of the whole exam using which they can navigate to the desired location and then switch to fine slice mode to obtain full details. This requires different architecture of multi-resolution wavelet decomposition as compared to the well-known progressive multi-resolution wavelet decomposition.

The paper is organized as follows. In Section 2, we present the progressive thick slab paradigm along with a novel 3-D wavelet-like decomposition to generate thick slabs and compare it with well-known progressive multi-resolution 3-D wavelet decomposition. We present an efficient navigation scheme and the diagnostic workflow using thick slabs in Section 3. In Section 4, we present our proposed 3-D compression scheme and compare its compression ratio and decoding speed performance with that of JPEG-2000. We conclude by pointing out that the proposed 3-D compression scheme suits radiology applications better than JPEG-2000 by providing better compression performance and faster decoding along with a smart navigation scheme, thus improving the productivity of radiologists.

2. PROGRESSIVE THICK SLAB PARADIGM

It is well understood that wavelet based compression scheme involves progressive multi-resolution decomposition of the data which enables progressive decoding and hence the accessibility of data from low resolution to high resolution. Wavelet based compression is extremely useful in teleradiology applications where the data can be transferred progressively from low to high resolution over low bandwidth networks so that the perceived delay in viewing the images on the console by the radiologist is minimal. Within the framework of wavelet based compression, we introduce *progressive thick slab paradigm* which provides an efficient method of navigating through large 3-D medical data sets.

Figure 1 shows the conventional 3-D wavelet decomposition of a data volume up to 3 levels. The 3-D wavelet decomposition

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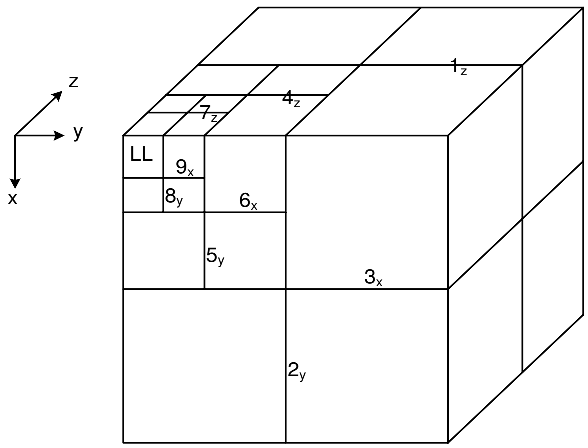

Fig. 1. Conventional 3-level progressive 3-D wavelet decomposition of a data volume. N in the notation N_s indicates the chronological order in which the wavelet transform is computed along direction s.

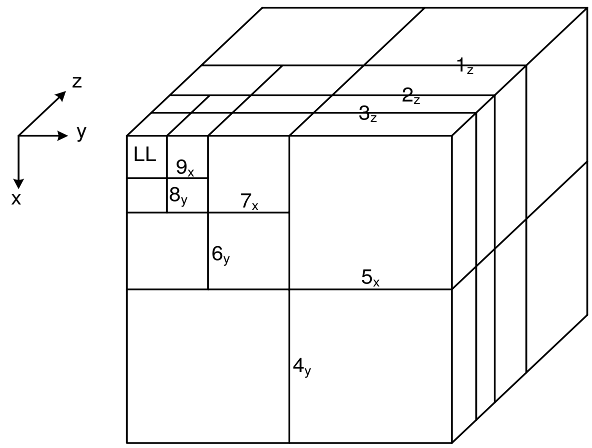

Fig. 2. Proposed 3-level 3-D wavelet decomposition of a data volume in thick slab paradigm. N in the notation N_s indicates the chronological order in which the wavelet transform is computed along direction s.

is implemented as separable 1-D decompositions along x, y and z directions. We refer to x-y plane as *spatial* direction and z axis as *axial* direction. The numbers $1-9$ and the subscripts x, y and z indicate the respective order and the orientation along which the wavelet decomposition is performed. The planes are chronologically ordered during the computation of forward transform and the reverse order has to be followed while computing the inverse transform. So, the notation 3_x indicates that the 3^{rd} step in the sequence of 9 steps involves the computation of wavelet transform along x-axis. The conventional 3-D wavelet decomposition involves the decomposition of 1-D data along x, y and z directions alternately at all scales. This means that the first level of wavelet decomposition is performed first along z direction, next along y and x directions. The second level of decomposition is then performed on the low-pass sub-volume or LLL sub-band in the similar way as in the first level of decomposition and the higher levels of decomposition are iterated on the low-pass sub-volume obtained from the previous level of decomposition. For a data volume with 8 slices, 3 levels of decomposition provide the LLL volume to be a low resolution image represented as LL in Figure 1. Consider a data volume of N slices which is divided into sub-volumes of 8 slices each. The conventional wavelet decomposition of each these sub-volumes provides LL images which can be considered as representative slices for respective sub-volumes and can be used in navigation of N slices (though effectively $\frac{N}{8}$ slices are used). But, radiologists would like to view at full resolution spatial data which would help them in diagnosis. Hence, the conventional wavelet decomposition cannot be used in compression framework for navigation application.

Figure 2 shows 3-levels of proposed 3-D wavelet-like multiresolution decomposition in thick slab paradigm of a data volume of 8 slices. We follow the same convention for the numbers $1-9$ and the subscripts x, y and z as discussed for Figure 1. The wavelet decomposition in thick slab paradigm involves complete wavelet decomposition along axial direction followed by spatial decompositions. The complete decomposition along axial direction provides a representative slice which we term as *thick slab*, as it provides the low resolution representation of the given data volume keeping the spatial resolution intact. This helps radiologists to navigate through large data sets without affecting their diagnostic capability. Radiologists look for average frames for faster navigation, which cannot be generated using conventional wavelet decomposition as all wavelet coefficients are required to compute the average frame, which means progressive decomposition is not utilized for thick slab generation. But, the proposed paradigm provides the average frame or thick slab during wavelet decomposition. The unique advantage of this paradigm is to provide images of multiple slice thickness without any duplication of data.

Having discussed the thick slab paradigm, it would be of interest to investigate the number of sub-bands generated by the conventional and thick slab 3-D wavelet decompositions. Let P and Q be the number of levels of decomposition along x-y and z directions respectively. Let R_c and R_t be the number of sub-bands obtained by using conventional and thick slab wavelet decomposition respectively. The number of sub-bands using conventional wavelet decomposition, R_c is given as

$$R_c = \begin{cases} 6P + Q + 1 & \text{for } P < Q \\ 7P + 1 & \text{for } P = Q \\ 3P + 4Q + 1 & \text{for } P > Q \end{cases} \tag{1}$$

The number of sub-bands using thick slab wavelet decomposition, R_t is given as

$$R_t = \begin{cases} \frac{3P}{2}(2Q - P + 3) + Q + 1 & \text{for } P < Q \\ \frac{P}{2}(3P + 11) + 1 & \text{for } P = Q \\ \frac{Q}{2}(3Q + 11) + 3(P - Q) + 1 & \text{for } P > Q \end{cases} \tag{2}$$

So, for the 3-level wavelet decompositions shown in Figure 1 and Figure 2, $R_c = 22$ and $R_t = 31$. It is clear that $R_t > R_c \; \forall \, P, Q$ except for $P = 0,\ Q \geq 0$ and $P \geq 0,\ 0 \leq Q \leq 1$ when $R_t = R_c$.

3. CLINICAL WORKFLOW AND NAVIGATION

The clinical workflow can best be understood under client-server architecture. Since the proposed paradigm works within the frame-

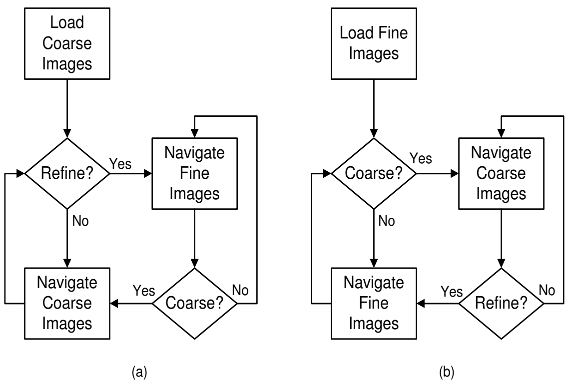

Fig. 3. Clinical workflow options for efficient navigation of large data sets. (a) Majority coarse workflow (b) Majority fine workflow

work of compression, let us assume that the compressed sub-volumes of a data volume are stored in a remote server. The workflow involves a client receiving information from the user (radiologist) regarding the resolution at which the data is to be viewed, depending on which, the client sends a request to the server requesting for the respective portion of the bit-stream, which is transmitted over the network. Upon receipt of the requested bit stream by the client, it is decoded and the corresponding image is provided to the user. Radiologists requiring low resolution images are provided with thick slabs, which can be used for navigation of the whole series instead of waiting for the whole volume to get decoded. The request for higher resolution images just requires the complementary bit stream to be transmitted, which is sufficient to generate the required higher resolution images, thus saving a lot of time in transmission over the network.

The clinical workflow options of majority coarse (low resolution/thick slabs) and majority fine (full resolution) are shown in Figure 3 which involve coarse-to-fine navigation and fine-to-coarse navigation. When presented with full resolution data, the fine-to-coarse workflow can be used to navigate to a particular location in the data set as lesser number of slices (low resolution data) need to be diagnosed instead of the full volume, thus saving radiologists' time. To improve the diagnosis, after reaching a particular location, the workflow has to be changed to coarse-to-fine so that the radiologists are presented with full resolution data for diagnosis.

Let us assume that a radiologist is to be provided with a 16-bit 3-D data set of 1600 slices of CT modality with each slice being 512×512 and 0.625 mm thick, which has to be transferred from a remote server over 100 MBPS network. Upon request of the radiologist, the transfer would take $\sim$ 8 minutes, assuming 20% network utilization for Ethernet. Instead of transferring the raw data, if $3 : 1$ compressed data is transferred over the same network, it involves a waiting time of ~ 3 minutes for the radiologist thus saving ~ 5 minutes when compared with the former scheme. Hence, a better compression scheme reduces radiologist's waiting time while improving his/her productivity. Once the data is transferred and is available for diagnosis, the radiologist may want to rapidly cine through the data set to reach a particular location to conduct diagnosis or provide diagnostic comments. Instead of navigating through the entire 1600 slices, the thick slab paradigm provides $\frac{1600}{8} = 200$ thick slabs which can be used to navigate to the desired location and then switch to fine slices using coarse-to-fine workflow to conduct diagnosis. This reduces the diagnosis time of radiologists aiding to improved productivity. It is obvious to understand that both high compression performance scheme and efficient navigation scheme are required to reduce the waiting and diagnosis times respectively. Though the thick slabs can be generated by just computing an average frame for each sub-volume, it does not provide good compression performance. The proposed 3-D decomposition in Figure 2 provides the navigation capability within the compression framework aiding to improved productivity of radiologists.

4. WAVELET BASED LOSSLESS VOLUMETRIC COMPRESSION WITH THICK SLAB DECOMPOSITION

Having discussed the need for 3-D compression and the smart navigation scheme provided by compression framework, we present the experimental results of compression ratio and decoding speed provided by our proposed volumetric compression scheme. Lossless compression is mostly preferred by radiologists because it does not degrade the image and also facilitates accurate diagnosis. Lossy compression techniques can lead to errors in diagnosis because in some cases they introduce unknown artifacts, although in most cases they achieve excellent visual quality. Furthermore, there exist several legal and regulatory issues that favor lossless compression in medical applications [2]. Hence, we used integer wavelet transforms obtained by the use of lifting scheme [3, 4] in our study with the thick slab decomposition shown in Figure 2. In order to achieve high compression ratio and fast decoding, we investigated

1. Integer 1-D wavelets to be used along axial and spatial directions. (We used same 1-D wavelet along x and y directions as the image resolution is same in both these directions)
2. Number of slices to form a sub-volume. (More number of slices would increase memory overhead)
3. Number of levels of decomposition. (The levels of decomposition along z direction depends on the number of slices used to form a sub-volume)

Three different integer 1-D wavelets, namely $(1, 1)$, $(2, 2)$ [3] and $(1 + 1, 1)$ [5] are considered for experimentation as they are less complex compared to wavelets with higher number of vanishing moments. 9 different 3-D wavelet combinations (3^2 combinations are possible with three 1-D wavelets and two orientations of spatial and axial) are investigated. Also, the number of frames to form a sub-volume is varied from 2 to 32 in powers of 2, which decides the number of levels of decomposition along z direction to be $\log_2$(number of frames). x and y directions are decomposed to such a level that the size of LL band is 64×64. In terms of compression ratio estimate and the decoding complexity, 3-D $(2, 2)$ wavelet with thick slab decomposition performed the best among all the combinations with 8 slices per sub-volume. The study is conducted on 3-D CT data sets with each 2-D slice being 512×512, which provides 3 levels ($\log_2\left(\frac{512}{64}\right) = 3$) of spatial decomposition. With the proposed combination of 8 frames per sub-volume and 3-D $(2, 2)$ wavelet, the wavelet coefficients are computed for each sub-volume of the data set. The detail $d_l[n]$ and approximation $s_l[n]$ coefficients for l^{th} level of decomposition with 1-D $(2, 2)$ wavelet transform are given by

$$d_{l+1}[n] = s_l[2n+1] - \left\lfloor \frac{s_l[2n] + s_l[2n+2] + 1}{2} \right\rfloor \quad (3)$$

Data	N_f	S_t	S_o	CR_{3D}	CR_J	CR_I
CT-1	232	5.000	75%	3.87	3.61	7.20%
CT-2	384	2.500	50%	3.59	3.44	4.36%
CT-3	1510	1.250	28%	3.87	3.86	0.26%
CT-4	1920	1.250	36%	3.91	3.90	0.26%
CT-5	2144	0.625	50%	3.21	3.11	3.21%

Table 1. Compression ratio performance of 3-D compression scheme w.r.t. JPEG-2000. N_f represents number of slices in the data volume, S_t and S_o represent the slice thickness (in mm) and slice overlap respectively, CR_{3D} and CR_J represent the compression ratio achieved by 3-D compression scheme and JPEG-2000 respectively. CR_I represents the percentage improvement in compression ratio of 3-D scheme over JPEG-2000, which is computed as $CR_I = \frac{CR_{3D}-CR_J}{CR_J} \times 100$.

$$s_{l+1}[n] = s_l[2n] + \left\lfloor \frac{d_{l+1}[n-1] + d_{l+1}[n] + 2}{4} \right\rfloor \quad (4)$$

where $0 \leq l < L$ and L represents the number of levels of decomposition. The sequence $s_0[n]$ is the original 1-D data on which $(2,2)$ wavelet coefficients are computed. As aforementioned, 3-D $(2,2)$ wavelet transform is implemented as three separable 1-D transforms, each along x, y and z directions and 3-D wavelet coefficients are computed. Huffman coding is used to code each of these coefficients and the bit-stream is generated in such a way that progressive decoding is achieved.

The compression ratio performance of our proposed 3-D compression scheme is compared to that of JPEG-2000 in Table 1. Table 2 shows the performance of 3-D compression scheme over JPEG-2000 in terms of decoding speed. It is to be noted that the performance comparison is made with respect to JPEG-2000 because it is the new state-of-the-art image compression standard designed for broad range of applications, including the compression and transmission of medical images. The decoding time results are obtained by running both compression schemes on a workstation with 1.7 GHz Intel Xenon processor and 512 MB RAM. It can be seen from Table 1 and Table 2 that the proposed lossless volumetric compression performs same or better than JPEG-2000 in terms of compression ratio and is 3 times as fast as JPEG-2000 in terms of decoding speed. JPEG-2000 uses adaptive arithmetic coding, which is more complex than the Huffman coding used in our proposed scheme. It is to be noted that better compression ratios can be achieved with our proposed method if more complex entropy coding schemes are adopted as in JPEG-2000, but with a trade-off in decoding speed. Compression schemes with fast decoder provide minimal waiting time for the radiologists when the data transferred over the network is progressively decoded, thus improving their productivity. Radiology applications prefer fast compression schemes with good compression performance. Hence, we argue that the proposed method suits radiology applications better than JPEG-2000 as it provides high compression performance with fast decoding capability along with a smart navigation scheme.

5. DISCUSSION & CONCLUSION

We have proposed a 3-D wavelet based lossless volumetric compression scheme which provides an efficient method to cine through large 3-D medical data sets. The conventional 3-D wavelet decomposition lacks the ability to provide an efficient navigation scheme, for which the thick slab wavelet decomposition is proposed. The proposed method is intended to improve the productivity of radiologists and suits radiology applications better than JPEG-2000 by providing better compression ratio and faster decoding along with clinical workflow options for smart navigation of large data sets. Though the results of the proposed method are provided only on computed tomography data sets, the method is also applicable to 3-D medical data sets of other modalities like magnetic resonance. The proposed scheme may not provide better compression ratio performance on non-overlapping data, time-varying data, ultrasound data etc. because of less correlation along axial direction.

Data	N_f	S_t	S_o	t_{3D}	t_J	$\frac{t_J}{t_{3D}}$
CT-1	232	5.000	75%	43.21	130.17	3.01
CT-2	384	2.500	50%	44.28	132.63	3.00
CT-3	1510	1.250	28%	43.41	124.77	2.87
CT-4	1920	1.250	36%	46.80	139.67	2.98
CT-5	2144	0.625	50%	43.17	124.53	2.88

Table 2. Decoding speed performance of 3-D compression scheme w.r.t. JPEG-2000. t_{3D} and t_J represent the decoding time per frame (in ms) achieved by 3-D compression scheme and JPEG-2000 respectively. The ratio $\frac{t_J}{t_{3D}}$ indicates the factor by which 3-D scheme is as fast as JPEG-2000.

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