REAL-TIME RENDERING OF TIME-VARYING VOLUME DATA USING A SINGLE COTS COMPUTER

Daisuke Nagayasu, Fumihiko Ino and Kenichi Hagihara
Graduate School of Information Science and Technology, Osaka University
1-3 Machikaneyama, Toyonaka, 560-8531 Osaka, Japan

Keywords: Volume rendering, time-varying data, pipelined rendering, data compression, GPU, COTS.

Abstract: This paper presents performance results of an out-of-core renderer, aiming at investigating the possibility of real-time rendering of time-varying scalar volume data using a single commercial off-the-shelf (COTS) computer. Our renderer is accelerated using software techniques such as data compression methods and thread-based pipeline mechanisms. These techniques are efficiently implemented on a COTS computer that combines multiple GPUs, CPUs, and storage devices using scalable link interface (SLI), multi-core, and redundant arrays of inexpensive disks (RAID) technologies, respectively. We find that the COTS-based out-of-core renderer achieves a video rate of 35 frames per second (fps) for $258 \times 258 \times 208$ voxel data with 99 time steps. It also demonstrates an almost interactive rate of 4 fps for $512 \times 512 \times 295$ voxel data with 411 time steps.

1 INTRODUCTION

Volume rendering of time-varying data plays an increasingly important role for understanding complex time-varying phenomena in a wide range of fields such as physical science and life science. This visualization technique produces animation sequences that show how the three-dimensional (3-D) structure evolves over time. Therefore, real-time rendering with interactive rates is necessary to assist scientists effectively in time-series analysis.

Due to the higher complexity of rendering tasks, real-time rendering systems have traditionally been implemented using high-performance computing (HPC) infrastructures such as supercomputers and clusters of PCs. However, recent rapid advances in graphics processing unit (GPU) technology (Montrym and Moreton, 2005) have allowed us to use a single commercial off-the-shelf (COTS) computer for dealing with real-time rendering of non-time-varying volume.

With respect to time-varying volume, on the other hand, we further require a fast I/O mechanism to achieve full performance on the GPU, because time-varying data usually cannot be stored entirely in the main memory. The lack of such an I/O mechanism will result in poor performance, because the GPU usually waits for the data for the next time step.

To address this problem, prior systems (Lum et al., 2002; Akiba et al., 2005; Strengert et al., 2005) reduced data size by data compression methods and minimized I/O time using RAID technology (Patterson et al., 1988). Some HPC-based systems (Chiueh and Ma, 1997; Bethel et al., 2000; Kniss et al., 2001; Yu and Ma, 2005) also increased the throughput by a pipeline mechanism that overlaps I/O operations with computation.

Thus, many researchers have tried to achieve real-time rendering of time-varying volume. However, it is still not clear how well each technique contributes to the acceleration. Furthermore, to the best of our knowledge, most of the systems are implemented on HPC systems. The objective of our project is to clarify the contribution of each technique and to provide a low-cost solution based on a single COTS computer.

In this paper, we present performance results of an out-of-core renderer, aiming at investigating the possibility of real-time rendering of time-varying scalar volume data using a single COTS computer. Our renderer is accelerated using well-known techniques such as data compression methods and thread-based pipeline mechanisms. These techniques are effi-

Nagayasu D., Ino F. and Hagihara K. (2007).
REAL-TIME RENDERING OF TIME-VARYING VOLUME DATA USING A SINGLE COTS COMPUTER.
In *Proceedings of the Second International Conference on Computer Graphics Theory and Applications - GM/R*, pages 220-227
DOI: 10.5220/0002076502200227

ciently implemented on a COTS computer that combines multiple GPUs, CPUs, and storage devices using scalable link interface (SLI) (nVIDIA Corporation, 2006), multi-core, and RAID technologies, respectively. The key contribution of this paper is to demonstrate that the techniques mentioned above are necessary to achieve real-time out-of-core rendering on a recent COTS computer.

The rest of the paper is organized as follows. Section 2 presents a model that abstracts a COTS computer. Section 3 describes our renderer with its underlying acceleration techniques. Section 4 presents performance results obtained on a COTS computer. Section 5 concludes the paper.

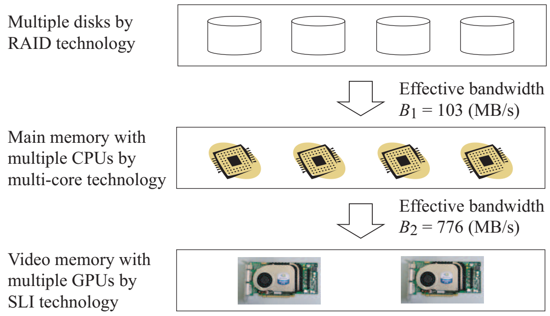


Figure 1: COTS computer model with hierarchical storage devices. This model assumes that the computer has multiple disks, CPUs, and GPUs to exploit data-parallelism in an out-of-core rendering task.

2 COTS COMPUTER MODEL

We first present a COTS computer model to design an efficient real-time renderer on a COTS system. Figure 1 shows the model. We regard a COTS system as a computer with hierarchical storages, having (1) multiple disks, (2) main memory with multiple CPUs, and (3) video memory with multiple GPUs. These hierarchical storages are connected by two buses, each with different bandwidths B_1 and B_2, where B_1 and B_2 represent the bandwidth from disks to main memory and that from main memory to video memory, respectively. For example, our COTS system presented later in Section 4 has $B_1 = 103$ and $B_2 = 776$ (MB/s).

Multiple disks can be realized using RAID technology (Patterson et al., 1988) at a low cost. We assume that COTS systems have a RAID 0 array of disk drives, where each disk drive separately stores different parts of a file. This configuration maximizes I/O bandwidth, because different parts can be loaded simultaneously from different drives. However, I/O latency is limited by the seek time of a single drive. Therefore, data size should be large enough to make the seek time relatively small over the entire I/O time. Thus, RAID technology reduces I/O time by increasing I/O bandwidth between storage devices and main memory.

Similarly, multiplication of the remaining components also can be realized by recent COTS technologies at a low cost. Multi-core and SLI technologies (nVIDIA Corporation, 2006) allow us to combine multiple CPUs and GPUs into a single computer, respectively. Note here that multiplication is done also in a single GPU. That is, GPUs have multiple shaders to exploit data parallelism in a rendering task (Montrym and Moreton, 2005).

Thus, our COTS model multiplies key components in a single computer. This multiplication can be regarded as a low-cost parallel architecture, as compared with HPC systems. From this viewpoint, clusters of PCs are also a low-cost solution. However, clusters are distributed-memory machines, which require image compositing after parallel rendering (Molnar et al., 1994). This involves high-overhead communication at every frame, and moreover, it takes longer time as the number of PCs increases (Ma et al., 1994). Therefore, we think that our COTS model is a reasonable solution in terms of cost and parallelism.

3 COTS-BASED OUT-OF-CORE RENDERER

In this section, we describe our renderer designed on the basis of the COTS model presented in Section 2. Figure 2 shows an overview of our pipelined renderer.

3.1 Design Aspects

Since out-of-core rendering systems must stream data through the two buses with different bandwidths B_1 and B_2, we need some mechanisms to deal with this bandwidth gap. Otherwise, the entire performance will be limited by the slower bus, and thus, the GPU and CPU might become idle during rendering.

The key idea to overcome this gap is to use a two-stage compression method, which performs data decompression both on the CPU and the GPU. In this method, the raw data must be converted into doubly-compressed data in advance of rendering. During rendering, the doubly-compressed data is decompressed firstly by the CPU, and then by the GPU. This two-stage method aims at hiding the gap by adjusting data size to the bandwidth. Therefore, the maximum performance will be achieved if the CPU generates

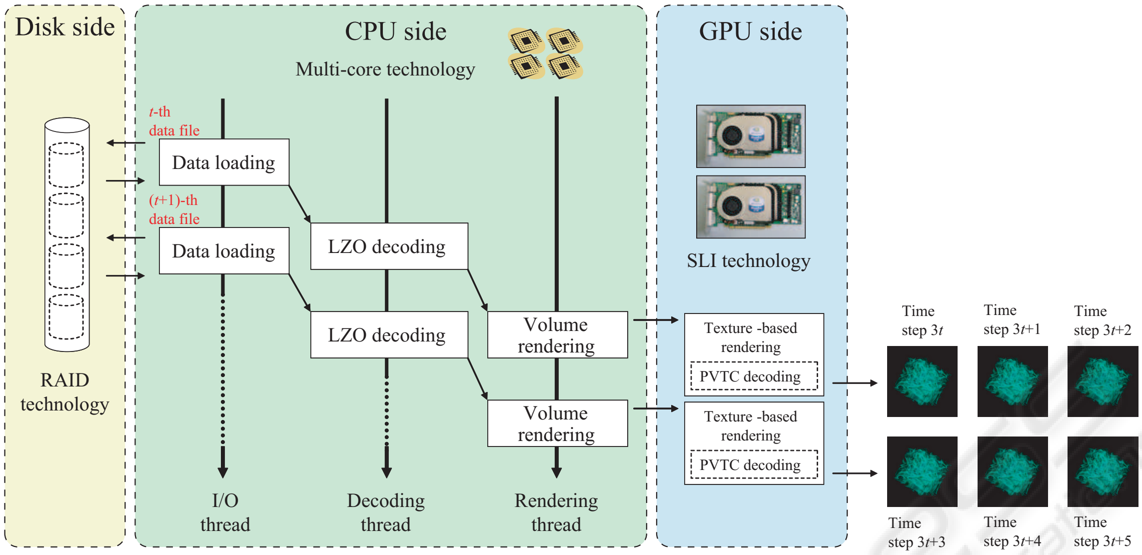


Figure 2: Overview of our pipelined rendering. The pipeline consists of three stages, each for data loading, LZO decoding, and volume rendering. Doubly-compressed data is stored in disks as a file, containing successive volumes for three time steps.

B_2/B_1 times larger data as compared with the doubly-compressed data loaded from disks.

We also use a pipeline mechanism to overlap I/O operations with computation. This mechanism increases the throughput of the renderer, because it allows us to process successive data simultaneously at different pipeline stages. In addition, the pipeline mechanism contributes to hide the decompression overheads incurred on the CPU.

Finally, once the time-varying data is sent to the GPU, the final image will be quickly generated by the GPU. Our renderer uses a texture-based rendering method (Cabral et al., 1994; Hadwiger et al., 2002), which is fully accelerated by hardware components in the GPU, such as texture mapping and alpha blending hardware. We currently use 3-D textures rather than 2-D textures, because 2-D textures require three times larger data (Hadwiger et al., 2002). Although this might be a trivial problem for rendering of non-time-varying data, it is critical for out-of-core (data-intensive) rendering.

3.2 Two-Stage Data Compression

As shown in Figure 2, the two-stage compression method performs data decompression both on the CPU and the GPU. At the CPU side, we use Lempel-Ziv-Oberhumer (LZO) compression (Oberhumer, 2005). On the other hand, we use packed volume texture compression (PVTC) at the GPU side. Thus, the raw data is firstly compressed by PVTC, and then by LZO.

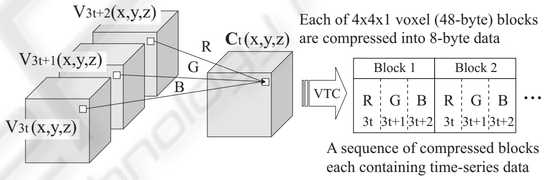


Figure 3: Data compression using PVTC. Time-series scalar voxels in the same location are packed into an RGB voxel. This data packing generates a sequence of compressed blocks, each containing time-series data.

This combination of different compression methods aims at taking architectural advantages of each processing unit. As compared with the GPU, the CPU has a memory hierarchy consisting of larger L1 and L2 cache and memory. These larger devices are suited to LZO decompression, because it is based on dictionary-based decoder (Ziv and Lempel, 1977), which simply repeats data replication during decompression.

In contrast, the GPU is based on a parallel architecture capable of vector processing and single instruction, multiple data (SIMD) processing (Montrym and Moreton, 2005). This architecture exploits higher parallelism than the CPU. Furthermore, some GPUs have special hardware, such as a volume texture compression (VTC) decoder (OpenGL Extension Registry, 2004), which provides us on-the-fly decompression of compressed texture. These architectural advantages are fully utilized by PVTC, which is an extension of VTC. As shown in Figure 3, the dif-

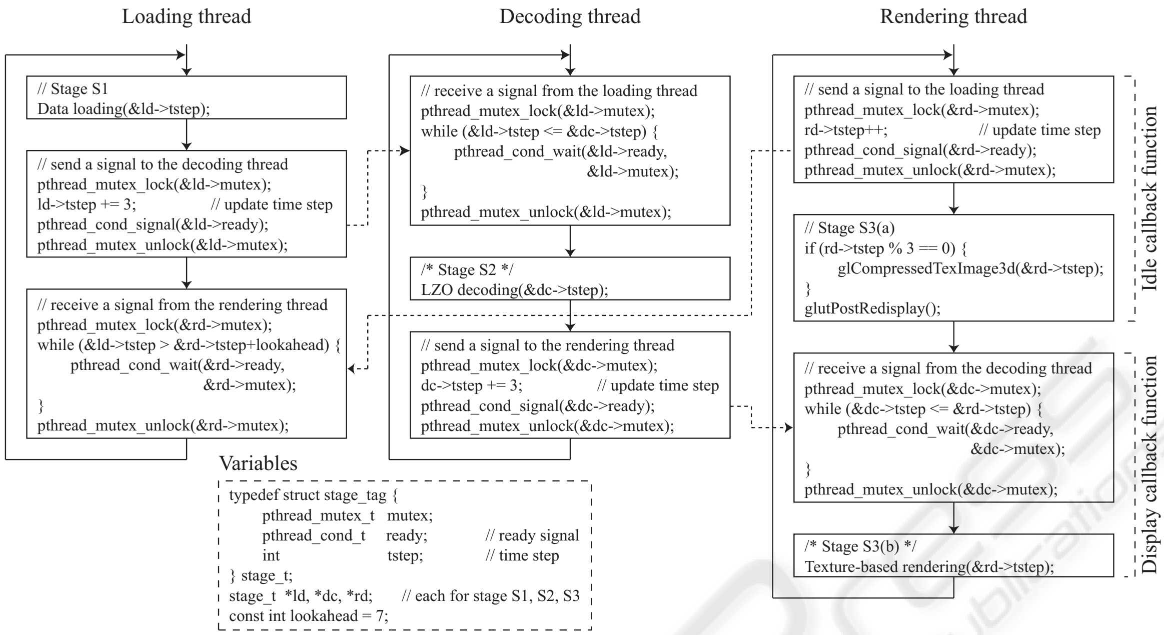


Figure 4: Pseudocode of our thread-based pipeline mechanism. See text for details. Variable 'lookahead' limits the number of stream data in the pipeline. This pipeline is allowed to process nine time steps of the data simultaneously, because each of the three stages can have the data containing three time steps.

ference to VTC is that PVTC packs three successive scalar volumes into an RGB-channel volume in advance of VTC. This data packing aims at exploiting the temporal coherence in time-varying volume data.

The doubly-compressed data is obtained by the following two steps (see also Figure 3).

1. PVTC compression. Three successive scalar volumes are packed into R, G, and B channels of a single volume, respectively. The packed data is converted into a compressed texture by VTC. Regardless of data contents, the compression ratio is fixed at a factor of 6, because VTC is a lossy compression method.
2. LZO compression. The compressed texture is further compressed by lossless LZO compression to generate doubly-compressed data. The compression ratio achieved by LZO depends on the coherence in the compressed texture.

In the rendering phase, the doubly-compressed data is decoded by the following three stages.

S1. Data loading from disks. Doubly-compressed data is loaded from disks to main memory. Note here that a loaded file contains three successive volumes due to PVTC data packing.

S2. LZO decoding on the CPU. The doubly-compressed data is decompressed by LZO. A compressed texture is then generated.

S3. Volume rendering on the GPU.

(a) Texture transfer. The compressed texture is sent from main memory to video memory.

(b) Texture-based rendering. Volumes stored in R, G, and B channels of the compressed texture are rendered successively. Hardware-accelerated on-the-fly decompression is provided by the VTC decoder.

Note here that PVTC reduces not only data size but also the number of data loads from disks, because it packs three volumes into a volume, namely a file. Similarly, the number of data transfers from main memory to video memory is also reduced to 1/3. These reductions allow us to minimize overheads required for I/O operations and texture transfers.

3.3 Pipeline Mechanism

Our pipeline mechanism intends to increase the rendering throughput by overlapping I/O operations with computation, as shown in Figure 2. To realize this mechanism by software, we use the POSIX thread library (Nichols et al., 1996). Our renderer creates three threads for each of stages S1, S2, and S3: the loading thread, the decoding thread, and the rendering thread, as shown in Figure 4.

This mechanism is thread-safe if the following conditions C1 and C2 are satisfied during execution.

Table 1: Storage devices used for experiments.

Component	Specification	Latency (ms)	B_1: Bandwidth (MB/s)
Single disk	250GB SATA disk (Seagate Barracuda 7200.9)	13.8	57.0
RAID 0	Four 250GB SATA disks (Hitachi Deskstar T7K250)	12.8	103.3

Table 2: Datasets used for experiments.

Dataset	Volume size (voxel)	Time step	Raw file size per time step (MB)	Compression ratio		Coherence	
				PVTC	PVTC+LZO	Temporal	Spatial
D1: Small jet	$129 \times 129 \times 104$	99	1.7	6	12.0	Low	High
D2: Small vortex	$128 \times 128 \times 128$	99	2.0		6.5	Low	Low
D3: Middle lung	$256 \times 256 \times 148$	411	9.3		67.0	High	High
D4: Middle jet	$258 \times 258 \times 208$	99	13.2		22.5	Low	High
D5: Middle vortex	$256 \times 256 \times 256$	99	16.0		12.0	Low	Low
D6: Large lung	$512 \times 512 \times 295$	411	73.8		71.7	High	High

C1. For all time steps t, the volume at time step t is processed sequentially from stage S1 to stage S3.

C2. The rendering thread produces images in an ascending order of time step t.

To satisfy condition C1, we create threads such that each of the threads is blocked with pthread_cond_wait() until it receives a signal from the upper thread. The upper thread, on the other hand, sends a signal to the lower thread when it finishes the responsible task. Also, the rendering thread sends a wake-up signal to the loading thread after rendering.

Condition C2 can be satisfied by implementing a first-in, first-out (FIFO) policy. To realize this, each thread has variable 'tstep,' which stores the latest time step processed at the corresponding stage. This information is then used to prevent the stream data from overtaking each other. That is, each thread is allowed to process the t-th data if it is already processed by the upper threads. Otherwise, it is repeatedly blocked with pthread_cond_wait() placed in a while loop.

4 EXPERIMENTAL RESULTS

We now show performance results of our renderer. We implemented it using the C++ language, the OpenGL library (Shreiner et al., 2003), the Cg toolkit (Mark et al., 2003), and the POSIX threads library (Nichols et al., 1996).

For experiments, we use a COTS computer equipped with 2 GB of main memory and 1 TB of Serial ATA disk devices shown in Table 1. The RAID array is constructed using nVIDIA RAID, which is included in nForce 590 SLI chipset. The computer has a Pentium D (dual-core) CPU running at 3 GHz clock speed and an nVIDIA GeForce 7900 GTX DDR SLI card having 512 MB of video memory. The graphics card is connected to a PCI Express 16X bus. The effective bandwidth B_2 is 776 MB/s.

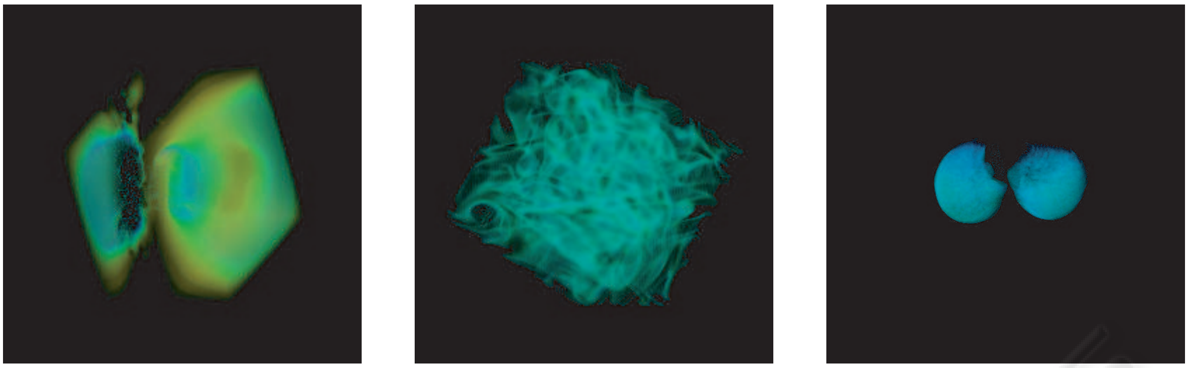
Table 2 summarizes six datasets D1–D6 used for experiments. See also Figure 5 for their visualization results. Datasets D1 and D2 (Ma, 2003) are fluid dynamics datasets showing a turbulent jet and a turbulent vortex flow, respectively. Dataset D3 shows a sequence of lung deformations representing a deformation process of nonrigid registration (Hajnal et al., 2001). The remaining datasets D4, D5, and D6 are high-resolution versions of D1, D2, and D3, respectively. Each dataset has voxels of 1-byte scalar data.

Datasets are rendered on a screen with an appropriate size: a 256×256 pixel screen for D1 and D2; a 512×512 pixel screen for D3, D4, and D5; and a 1024×1024 pixel screen for D6. The viewing direction is initially set to z-axis direction, and then it is rotated 2 degrees around x- and y-axes when the time step is updated.

4.1 Rendering Performance

To evaluate the performance gain of our renderer, we compare it with 11 variations that utilize only a part of the acceleration techniques: the RAID technology; the pipeline mechanism; and the two-stage compression method. In the following, notations 'R' and 'P' indicates the RAID-equipped renderer and the pipelined renderer, respectively. Notation 'N' represents the naive renderer without RAID and pipeline mechanisms.

Figure 6 shows frame rates for 12 renderers. We can see that the COTS-based out-of-core renderer achieves a video rate of 35 frames per second (fps) for $258 \times 258 \times 208$ voxel data with 99 time steps. It also demonstrates an almost interactive rate of 4 fps



(a) (b) (c)

Figure 5: Produced images using three datasets. (a) D1: turbulent jet, (b) D2: turbulent vortex flow, and (c) D3: deforming lung.

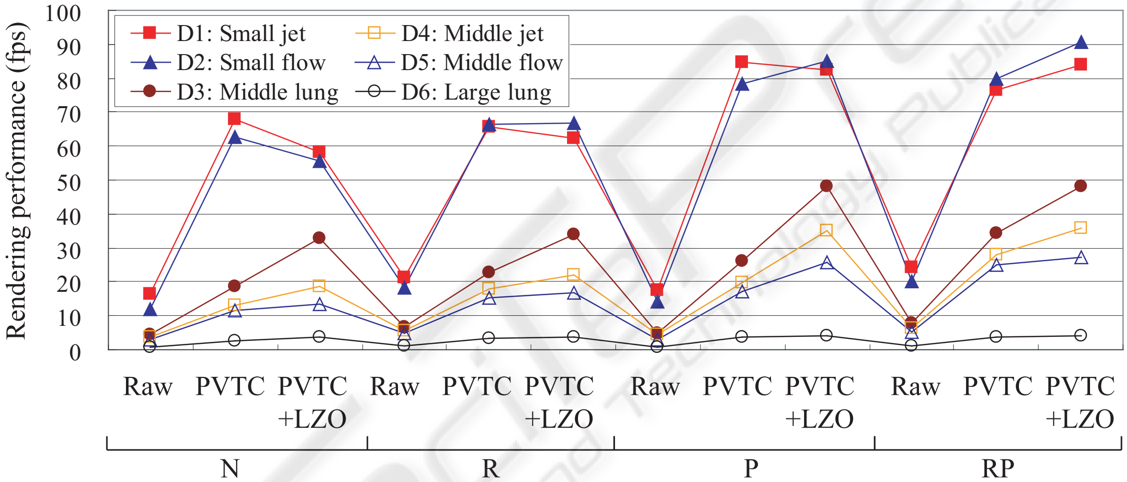


Figure 6: Rendering performance in frames per second (fps). Notations 'R' and 'P' indicates the RAID-equipped renderer and the pipelined renderer, respectively. Notation 'N' represents the naive renderer without RAID and pipeline mechanisms.

for $512 \times 512 \times 295$ voxel data with 411 time steps. These performance results are competitive with prior results (Akiba et al., 2005), which achieve 1.1 fps for $256 \times 256 \times 1024$ voxel data with 400 time steps.

Improvement achieved by the pipeline mechanism is not significant if I/O time is not reduced by compression or RAID. For example, the P renderer results in 1–17% improvement over the N renderer if compression methods are not used. In contrast, compression methods increase this improvement ratio to 3–91%. The RP renderer also increases the ratio to 49–73% by RAID. This means that most of the execution time is spent by I/O operations if we do not use compression or RAID. Therefore, overlapping I/O operations with other operations is not effective in this case. Thus, we must reduce I/O time by RAID and/or compression methods in order to maximize the performance benefits of the pipeline mechanism.

The improvement ratio of 3–91% also indicates that two-stage compression is effective especially on pipelined renderers. Such renderers allow us to overlap decompression overheads with I/O time, as we mentioned in Section 3.1.

4.2 Breakdown Analysis

Table 3 shows the total execution time T and its breakdown: T_d, T_l, and T_g. T_d and T_l here represent the time for data loading and LZO decompression, respectively. T_g is the time for texture-based rendering, including the time T_t for texture transfers.

Firstly, we analyze the effects of data compression

Table 3: Breakdown analysis of execution time. T represents the total execution time required for rendering of a volume at a certain time step. Times T_d, T_l, and T_g are the breakdown of time T, each representing the time for data loading, for LZO decompression, and for texture-based rendering. T_g includes time T_t for texture transfers.

Data-sets	Ren-derer	Raw				PVTC				PVTC+LZO				
		I/O	GPU			I/O	GPU			I/O	LZO	GPU		
		T_d	T_t	T_g	T	T_d	T_t	T_g	T	T_d	T_l	T_t	T_g	T
D1	N	53.4	4.4	4.7	61.6	11.0	1.5	2.2	14.7	11.1	2.3	1.5	2.3	17.2
	R	38.9	4.4	4.7	47.2	11.4	1.5	2.3	15.2	9.9	2.5	1.5	2.3	16.1
	P	56.1	4.5	5.0	56.9	11.2	1.4	1.8	11.8	11.6	1.7	1.4	1.7	12.1
	RP	40.5	4.6	5.2	41.3	12.5	1.4	1.8	13.1	11.4	1.7	1.4	1.7	11.9
D2	N	75.8	4.0	4.9	82.5	11.5	1.8	2.6	15.9	11.4	2.3	1.8	2.8	18.0
	R	48.0	3.9	4.9	54.6	10.6	1.9	2.8	15.0	8.5	2.5	1.8	2.9	15.0
	P	69.5	3.6	4.2	70.4	12.2	1.7	2.1	12.8	11.1	2.0	1.7	2.1	11.8
	RP	49.2	3.6	4.2	49.3	12.1	1.7	2.0	12.5	10.4	2.0	1.7	2.1	11.0
D3	N	188.9	13.3	13.7	215.9	38.2	8.2	11.5	53.8	12.1	2.9	8.2	11.4	30.5
	R	121.5	13.4	13.8	148.7	28.1	8.2	11.7	44.1	11.6	2.6	8.2	11.4	29.6
	P	204.6	14.6	15.6	205.5	37.5	8.1	8.5	38.2	12.8	2.7	8.3	15.7	20.8
	RP	128.3	14.1	15.0	129.1	28.3	8.1	8.7	29.1	11.8	2.8	8.0	15.3	20.7
D4	N	231.1	19.0	19.4	264.2	54.8	11.7	16.4	75.6	23.2	9.6	11.7	16.3	53.6
	R	142.8	19.0	19.4	175.6	35.3	11.8	16.4	56.1	16.0	8.8	11.8	17.1	45.1
	P	229.9	23.0	23.9	230.8	49.8	11.6	12.2	50.4	20.4	9.6	11.9	20.3	28.6
	RP	154.7	23.6	24.7	155.5	35.2	11.7	12.4	35.7	16.9	9.5	11.9	21.1	27.9
D5	N	294.9	25.8	26.2	325.5	58.2	14.4	20.4	85.4	33.9	13.3	14.1	20.0	73.7
	R	174.8	25.7	26.2	205.3	38.7	14.2	20.1	65.1	20.4	12.9	14.1	20.1	59.8
	P	322.9	27.0	28.1	323.8	57.7	14.9	15.5	58.3	34.2	13.3	14.8	24.6	38.7
	RP	193.3	31.7	32.7	194.0	38.7	14.9	21.7	40.1	22.7	13.6	15.1	28.1	36.9
D6	N	1360.8	102.9	104.0	1482.5	207.2	65.1	125.6	366.9	26.6	19.7	121.2	183.0	261.9
	R	766.0	102.8	103.9	895.3	137.4	67.5	127.0	299.9	19.6	19.4	126.3	187.9	260.2
	P	1445.2	134.4	136.1	1446.1	209.7	93.6	196.0	270.7	27.0	20.7	91.9	216.4	253.6
	RP	855.2	133.8	135.5	856.1	140.0	93.2	208.7	260.1	21.3	22.2	91.8	215.6	253.2

methods on the N renderer. In Table 3, we can see that PVTC achieves 3.5–5.2 times higher performance, as compared to the raw renderer. Furthermore, the combination of PVTC and LZO achieves 1.2–1.8 times higher performance than PVTC for datasets D3, D4, D5, and D6. This performance gain is obtained by the reduction of time T_d. For D1 and D2, however, this combination fails to show the performance gain over PVTC. This is mainly due to the small file size. For such small datasets, I/O time is mainly limited by I/O latency, as we mentioned in Section 2. Therefore, the renderer fails to reduce time T_d, and moreover, it increases time T_l due to the decompression overheads.

Secondly, we compare the N renderer with the P renderer to analyze the effects of the pipeline mechanism. In the N renderer, T_d, T_l, and T_g accounts for most of the entire time T. In contrast, the P renderer overlaps these three overheads to reduce the entire time T. As a result, it achieves a 1.9-fold speedup over the N renderer at the best case. In many cases, this pipeline mechanism reduces the entire time T roughly to time T_d, because the data loading stage is the bottleneck stage in the pipeline. Therefore, the decompression cost T_l is usually hidden by time T_d. Thus, the pipeline mechanism is capable of hiding the overheads of the two-stage compression method.

Finally, we compare the N renderer with the R renderer to analyze the effects of RAID technology. This technology reduces time T_d by approximately 30% for larger datasets. On the other hand, it fails to reduce time T_d if it is approximately 10 ms. This result is reasonable because the threshold of 10 ms is close to the I/O latency of a single disk shown in Table 1. Thus, RAID technology is useful if the data file is large enough to distribute it to every disk in the RAID array.

5 CONCLUSION

We have presented performance results of an out-of-core renderer for time-varying volume. Our renderer is based on two software-based techniques that increase the performance: (1) a two-stage data compression method and (2) a thread-based pipeline mechanism. The renderer is implemented efficiently on a recent COTS computer equipped with multiple GPUs, CPUs, and storage devices using SLI, multi-core, and RAID technologies, respectively.

Experimental results indicate that the COTS-based out-of-core renderer achieves a video rate of 35 frames per second (fps) for $258 \times 258 \times 208$ voxel data with 99 time steps. It also demonstrates an almost interactive rate of 4 fps for $512 \times 512 \times 295$ voxel data with 411 time steps. These performance results are competitive with prior results.

We also find that most of the execution time is spent by I/O operations if we do not use compression or RAID. Therefore, we think that I/O time must be reduced by RAID and/or compression methods in order to maximize the performance benefit of the pipeline mechanism. The two stage compression method achieves 3.6–7.1 times higher rendering performance than the raw renderer. By integrating this method into the pipeline mechanism, it achieves a 1.9-fold speedup at the best case. We think that the pipeline mechanism is useful to hide the overheads of data decompression.

One future work is to present performance comparison with traditional HPC-based renderers.

ACKNOWLEDGEMENTS

This work was partly supported by JSPS Grant-in-Aid for Scientific Research for Scientific Research (B)(2)(18300009) and on Priority Areas (17032007). We would like to thank the anonymous reviewers for their valuable comments.

REFERENCES

Akiba, H., Ma, K.-L., and Clyne, J. (2005). End-to-end data reduction and hardware accelerated rendering techniques for visualizing time-varying non-uniform grid volume data. In *Proc. 4th Int'l Workshop Volume Graphics (VG'05)*, pages 31–39.

Bethel, W., Tierney, B., Lee, J., Gunter, D., and Lau, S. (2000). Using high-speed WANs and network data caches to enable remote and distributed visualization. In *Proc. High Performance Networking and Computing Conf. (SC'00)*, 23 pages (CD-ROM).

Cabral, B., Cam, N., and Foran, J. (1994). Accelerated volume rendering and tomographic reconstruction using texture mapping hardware. In *Proc. 4th Symp. Volume Visualization (VVS'94)*, pages 91–98.

Chiueh, T. and Ma, K.-L. (1997). A parallel pipelined renderer for time-varying volume data. In *Proc. 2nd Int'l Symp. Parallel Architectures, Algorithms and Networks (I-SPAN'97)*, pages 9–15.

Hadwiger, M., Kniss, J. M., Engel, K., and Rezk-Salama, C. (2002). High-quality volume graphics on consumer PC hardware. In *SIGGRAPH 2002, Course Notes 42*.

Hajnal, J. V., Hill, D. L., and Hawkes, D. J., editors (2001). *Medical Image Registration*. CRC Press, Boca Raton, FL.

Kniss, J., McCormick, P., McPherson, A., Ahrens, J., Painter, J., Keahey, A., and Hansen, C. (2001). Interactive texture-based volume rendering for large data sets. *IEEE Computer Graphics and Applications*, 21(4):52–61.

Lum, E. B., Ma, K.-L., and Clyne, J. (2002). A hardware-assisted scalable solution for interactive volume rendering of time-varying data. *IEEE Trans. Visualization and Computer Graphics*, 8(3):286–301.

Ma, K.-L. (2003). Time-Varying Volume Data Repository. http://www.cs.ucdavis. edu/˜ ma/ITR/tvdr.html.

Ma, K.-L., Painter, J. S., Hansen, C. D., and Krogh, M. F. (1994). Parallel volume rendering using binary-swap compositing. *IEEE Computer Graphics and Applications*, 14(4):59–68.

Mark, W. R., Glanville, R. S., Akeley, K., and Kilgard, M. J. (2003). Cg: A system for programming graphics hardware in a C-like language. *ACM Trans. Graphics*, 22(3):896–897.

Molnar, S., Cox, M., Ellsworth, D., and Fuchs, H. (1994). A sorting classification of parallel rendering. *IEEE Computer Graphics and Applications*, 14(4):23–32.

Montrym, J. and Moreton, H. (2005). The GeForce 6800. *IEEE Micro*, 25(2):41–51.

Nichols, B., Buttlar, B., and Farrell, J. P. (1996). *Pthreads Programming*. O'Reilly & Associates, Newton, MA.

nVIDIA Corporation (2006). nVIDIA SLI. http://www.slizone.com/.

Oberhumer, M.F.X.J. (2005). LZO real-time data compression library. http://www.oberhumer.com/ opensource/lzo/.

OpenGL Extension Registry (2004). Gl_nv_texture_compression_vtc. http://oss.sgi.com/projects/ogl-sample/registry/NV/texture_compression_%vtc.txt.

Patterson, D. A., Gibson, G. A., and Katz, R. H. (1988). A case for redundant arrays of inexpensive disks (RAID). In *Proc. the ACM SIGMOD Int. Conf. Management of Data (SIGMOD '88)*, pages 109–116.

Shreiner, D., Woo, M., Neider, J., and Davis, T. (2003). *OpenGL Programming Guide*. Addison-Wesley, Reading, MA, fourth edition.

Strengert, M., Magallón, M., Weiskopf, D., Guthe, S., and Ertl, T. (2005). Large volume visualization of compressed time-dependent datasets on GPU clusters. *Parallel Computing*, 31(2):205–219.

Yu, H. and Ma, K.-L. (2005). A study of I/O methods for parallel visualization of large-scale data. *Parallel Computing*, 31(2):167–183.

Ziv, J. and Lempel, A. (1977). A universal algorithm for sequential data compression. *IEEE Trans. Information Theory*, 23(3):337–343.