Real-Time Reconstruction for 3D CT Applied to Big Objects of Cultural Heritage

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Abstract
Computed Tomography is a non-destructive technique for which the object volume is reconstructed from a large series of radiographs acquired at different angles. Information can be retrieved as 2D cross section images allowing the inspection and the classification of the object; moreover, by processing tomographic data, a 3D numerical model of the full-volume sample can be obtained for virtual reality applications or digital archives storage. Computed Tomography is well known, specially in the medical field. However, it is a complex technique as soon as one wants to use it in a different way than in medicine (that means different scale, different energy range, different material composition and so on). The Kongo Rikishi is a Japanese wooden statue (over 200 cm of height) of the XIII century. The restoration has been carried out by the Conservation and Restoration Center La Venaria Reale, Turin, Italy. An high resolution Computed Tomography has been realized by the X-Ray Imaging Group of the Physics Department of Bologna University, Italy. To investigate the entire statue volume, up to 36 shootings are needed and for each of them 720 radiographs are acquired. To obtain the final volume (120 GB) 30 days of calculation are needed with a standard PC. In this work we will show the Proof of Concept that we have done using the Microsoft HPC cluster in Redmond. The Microsoft HPC environment has proved to be dramatically powerful and easy to use letting us reach important results quickly. Simply running many copies of the same software on different chunks of data using 20 cores has lead to an impressive speedup: up to a speed factor of 28. The same code, running on a new generation cluster of 32 cores, completed the elaborations with a speed rate factor of 75. These extraordinary results permit to reconstruct the volume in 6 hours instead of 30 days, making possible the real-time investigation of cultural objects.
Keywords: 3D Computed Tomography, Parallelization, HPC-Cluster, Reconstruction, Imaging

1. Introduction

The Kongo Rikishi, “the Temple Guardian”, is a Japanese wooden statue of the XIII century, Kamamura period [1]. The restoration has been carried out by the Conservation and Restoration Center “*La Venaria Reale*” funded by the “*Compagnia di San Paolo per l’Arte*” in Turin, Italy. Several different diagnostic techniques are applied to estimate the conservation condition of the statue. In particular an high resolution Computed Tomography (CT) has been realized by the X-Ray Imaging Group of the Physics Department of Bologna University, Italy.

The CT is a non-destructive technique for which several radiographs of the investigated objects are acquired at different angles. The acquired images are then elaborated to reconstruct the volume of the object. The reconstructed volume is composed by slices.

X-ray Computed Tomography (CT) can be applied successfully to cultural heritage to obtain morphological and physical information of the inner structure of archaeological samples [2]. Information can be retrieved as 2D cross section images or 3D full-volume images allowing the inspection and the classification of the object; moreover, by processing tomographic data [3], a 3D numerical model of the sample can be obtained for virtual reality applications or digital archives storage. Computed Tomography is well known, specially in the medical field. However, it is a complex technique and as soon as one wants to use it in a different way

than in medicine (that means different scale, different energy range, different material composition and so on) a lot of problems suddenly arise.
The dimensions of the Kongo Rikishi are 205 cm high, 100 cm length and 42 cm depth; the basement is 36 cm high, 118 cm length, 76 cm depth. The tomographyc system realized to investigate the statue is shown in Figure 1.a). The tomographyc system is composed by an X-ray source (200 KVp), a detector of 450 × 450 mm^2 (CsI screen coupled with a CCD camera by means of a mirror and a lens system), a mechanics structure able to translate the tube and the detector and a electronics rotating platform for the statue. Because of the detector sizes are 450 mm × 450 mm it is necessary to divide the entire statue in 12 horizontal sections. Then the detector has been placed at fixed height and for each section the detector has been horizontal translated to acquired the radiographies at different shootings. For each shooting the statue has been rotated by a step of 0,5° over the 360° angle. Then 720 images have been acquired fro each shooting. The scheme of the analysis is shown in Figure 1.b). Has been acquired 25920 radiographs. Each radiograph is a digital image of 1092 × 736 pixels at 12 bit. All data related to acquisition is shown in Table 1.

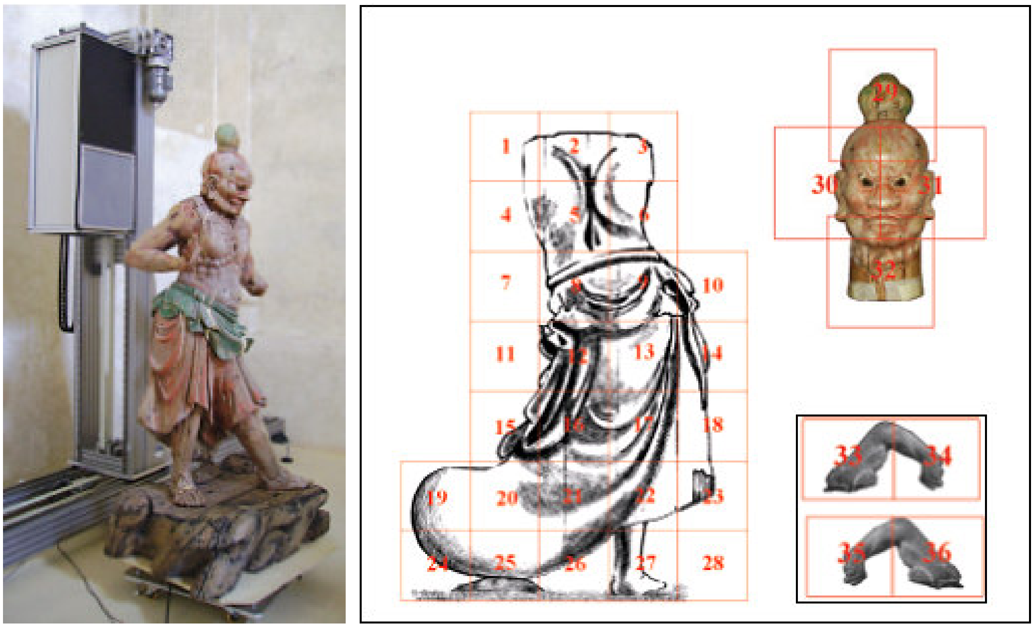

Figure 1 – a) Picture of the Kongo Rikishi statue during the measurements (left);
b) scheme of the sections and the shootings.

Data about tomographyc acquisition	
N° of sections	12
N° of shootings	36
Radiographs / Shooting	720
Total N° of images	25920
N° of pixel for image	1092 × 736
Pixel Depth	12 bit
Mbyte for image	1.53
Gbyte total	38.80
T-scan shooting	47 minutes
T-scan entire statue	28 hours

Table 1. Data about tomographyc acquisition

2. Comparison between HPC-Cluster and a Dual-Core PC

2.1 The computer systems compared

The entire data set of the Kongo has been reconstructed with a dual core pc and in several different tests on HPC Cluster. The technical data of the two systems are shown in Table 2.

Characteristic	PC located at Physics Department of Bologna University	HPC-Cluster, courtesy of Microsoft, Redmond:
Operative system	Windows Professional XP 2002 with SP2.	Windows Server HPC Edition 2007 with SP1.
Number and type of CPU	Intel Core™ 2 CPU	Intel Xeon 4 CPU
CPU and Frequency	6300 @ 1.86 GHz	E5335 @ 2GHz
Bit word	32-bit	64-bit
RAM	2GB	8 GB
Number of core per PC	2	4
Gbyte per core	1	2
Number of nodes	1	5

Table 2. Technical data concerning the two systems compared.

2.2 The tomographyc programs

The software program used to reconstruct the Kongo Rikishi volume is named Imgrec. This program is courtesy of Daniel Schnaberk of Lawrence Livermore National Laboratory. Imgrec provides all steps necessary to reconstruct the volume: calculation of the atenrads and the sinos, the ring filter and the reconstruction algorithm. This software is written in Labwindows/CVI and it is ANSI C. Imgrec has been used for this work in three forms:

1. the software compiled by LabWindows/CVI and with an user interface, Imgrec-UI;
2. the software compiled by LabWindows/CVI and with an user interface, but ran by a batch file, Imgrec-B;
3. the software compiled , as 32 bit or 64 bit, by Visual Studio 2008 without user interface and ran by command line, Imgrec-C-32 and Imgrec-C-64.

All Imgrec versions run on the basis of a configuration file containing all data needed to reconstruct the volume step by step. This configuration file is named SCT and the program creates another updated SCT file each time a step is done. Each step is realized executing an instruction.

1. Imgrec-UI is an interactive software controlled by user interface. Each instruction is executed and visualized on the monitor.
2. Imgrec-B reads the sequence of instructions to run from a batch files, but must be firstly started by user interface and then the instructions are executed without showing elaborated images.
3. Imgrec-C 32 and 64 are the software of Imgrec divided into steps. So each executable corresponding to only one instruction and runs without UI and without visualizing elaborated images.

The program ran at Physics Department is Imgrec-UI for steps from 2.2 to 2.4. For the step 2.5, the reconstruction, the program ran is Imgrec-B.

At HPC-Cluster the programs ran are Imgrec-UI, Imgrec-C-32 and Imgrec-C-64.

To achieve the first step, crop and collate of the projections, a C-software realized at Physics Department has been used. We named this software CMP.

2.3 HPC-Cluster solutions

Several different solutions were been implemented at HPC-Cluster. A very useful program, coming with SP1 of the Windows Server HPC Edition 2007, is the “Job Manager”. This utility is able to create, to manage and to save jobs, tasks and priorities. In particular the “Parametric Sweep Job” utility has used to run the same executable simultaneously on the 5 nodes available. In this approach some solutions have been adopted:

1. In order to minimize the time of the data transfer through network, local directories are created in each node. All local directories are named with an identical path and name.
2. The executable program has been copied on each node in the local directories.
3. The configuration SCT files have been copied in each local directories.
4. The SCT files are used to divided the work in tasks.

HPC-Cluster is placed at Redmond, WA. We accessed to it by means of “Remote Desktop Connection”.

3. Reconstruction Results

Please, note that all results for each algorithm steps will be presented at the conference.

Now for each step of the reconstruction algorithm the times spent are presented.

In order to introduce a measure to quantify the comparison, a speed rate factor SRF is defined as:

$$SRF = V_{HPC} / V_{Unibo} = T_{Unibo} / T_{HPC} \quad (1)$$

where V_{HPC} and V_{Unibo} are the speed on Unibo and on HPC-Cluster.

The rate speed factor is then a measure of the speed increase of the algorithm running on HPC-Cluster in front of the same algorithm running on a standard PC. Until now we refer to speed rate factor as SRF.

The latest step is the recostruction. This step implies a very large amount of calculations, thus this is the step for which the parallelization would obtain the best results. In table 3 the sizes of sinograms for each section and all data related to reconstruction are presented.

In table 14 the single task data and results are presented for all system.

Section	Name	Sinogram sizes (pixels × pixels)	Number of sinograms (and slices)	Sinogram (kBytes)	Slice reconstructed (kBytes)	All sinograms (GigaBytes)	All slices (GigaBytes)
1	Plume	696 × 720	611	1958	1893	1.14	1.10
2	Head	867 × 720	690	2439	2937	1.60	1.93
3	Neck	698 × 720	411	1964	1904	0.77	0.75
4	Shoulders	1500 × 720	584	4219	8790	2.35	4.90
5	Trunk	1494 × 720	721	4202	8719	2.89	6.00
6	Waist	2131 × 720	720	5994	17739	4.12	12.18
7	Clothing	2135 × 720	721	6005	17806	4.13	12.24
8	Legs A	2615 × 720	721	7355	26712	5.06	18.37
9	Legs B	3274 × 720	721	9209	41872	6.33	28.79
10	Feet	3170 × 720	721	8916	39254	6.13	26.99
11	Arm right	1358 × 720	531	3820	7204	1.93	3.65
12	Arm left	1335 × 720	722	3755	6962	2.59	4.79
					TOTAL:	**39.04**	**121.69**

Table 3. Data and sizes of sinograms and slices.

Section	Name	Number of sinograms	Slice reconstructed (kBytes)	Unibo / Imgrec-UI	HPC / Imgrec -C 32 bit		HPC / Imgrec -C 64 bit	
				Time per slice (s)	Time per slice (s)	SRF	Time per slice (s)	SRF
1	Plume	611	1893	24.18	20.86	1.16	15.41	1.57
2	Head	690	2937	45.97	39.03	1.18	28.74	1.60
3	Neck	411	1904	29.87	27.36	1.09	20.22	1.48
4	Shoulders	584	8790	136.84	126.68	1.08	92.37	1.48
5	Trunk	721	8719	138.31	125.11	1.11	90.91	1.52
6	Waist	720	17739	286.63	250.48	1.14	183.05	1.57
7	Clothing	721	17806	285.63	206.50	1.38	151.46	1.89
8	Legs A	721	26712	352.69	305.11	1.16	225.35	1.57
9	Legs B	721	41872	428.98	545.61	0.79	398.34	1.08
10	Feet	721	39254	598.18	522.98	1.14	381.24	1.57
11	Arm right	531	7204	117.61	102.78	1.14	74.72	1.57
12	Arm left	722	6962	109.67	95.90	1.14	69.84	1.57

Table 4. Times resulted for single task ran at Unibo or HPC 32/64 bit.

The elaborations of data in a single task show how the Unibo processor is more fast than the ones at HPC. In fact the SRF at 32 bit is 0.85, that is the Unibo processor is 15% more fast the ones at HPC. But when the calculations are carried out at 64 bit the improvement is of 22% in comparison with Unibo, that is if the HPC processors would be equal to Unibo one then the improvement will be of 44%.

Data				1 TASK	20 TASKS			
Section	Name	Number of sinograms	Slice (kBytes)	Unibo / Imgrec-UI	HPC / Imgrec -C 32 bit		HPC / Imgrec -C 64 bit	
				Time per slice (s)	Time per slice (s)	SRF	Time per slice (s)	SRF
1	Plume	611	1893	24.18	1.44	16.80	1.04	23.20
2	Head	690	2937	45.97	2.09	22.00	1.54	29.90
3	Neck	411	1904	29.87	1.45	20.70	1.06	28.10
4	Shoulders	584	8790	136.84	6.62	20.67	4.89	27.97
5	Trunk	721	8719	138.31	6.46	21.42	4.79	28.86
6	Waist	720	17739	286.63	12.82	22.35	9.50	30.16
7	Clothing	721	17806	285.63	13.07	21.86	9.60	29.48
8	Legs A	721	26712	352.69	16.77	21.03	12.75	27.67
9	Legs B	721	41872	428.98	28.10	15.27	20.43	20.99
9 bis	Legs B	721	41872	428.98	27.82	15.42	20.71	20.72
10	Feet	721	39254	598.18	27.45	21.80	19.58	30.55
11	Arm right	531	7204	117.61	7.26	16.20	5.30	22.19
12	Arm left	722	6962	109.67	5.06	21.67	3.68	29.79

Table 5. Times resulted for 20 tasks or HPC 32/64 bit.

At the end all 12 sections are reconstructed in parallel with different number of tasks.

System	Tasks	Bit	Total time (dd:hh:mm:ss)	SRF
Unibo	1	32	20:15:24:18	1
HPC	240	64	00:17:23:16	28.49
HPC	797	64	00:17:15:43	28.70
HPC	1594	64	00:17:14:18	28.74

Table 6. Times to reconstruct all 12 sections as functions of tasks number.

4. E4 Comparison and results

Characteristic	PC located at Physics Department of Bologna University	HPC-Cluster, courtesy of Microsoft, Redmond	E4 cluster, courtesy of E4, Bologna
Operative system	Windows Professional XP 2002 with SP2.	Windows Server HPC Edition 2007 with SP1	Windows Server HPC Edition 2008
Number and type of CPU	Intel Core™ 2 CPU	Intel Xeon 4 CPU	Intel Xeon 4 CPU
CPU and Frequency	6300 @ 1.86 GHz	E5335 @ 2GHz	E5520 @ 2.27 GHz (2 processors)
Bit word	32-bit	64-bit	64-bit
RAM	2GB	8 GB	6/12 GB
Number of core per PC	2	4	8
Gbyte per core	1	2	2/4
Number of nodes	1	5	4 (3 used)

Table 7. Technical data concerning the three systems compared.

4.3 Reconstruction step results

Section	**Unibo** **32 bit 1 task** **(dd:hh:mm:ss)**	**HPC** **64 bit 20 tasks** **20 cores** **(hh:mm:ss)**	**E4** **64 bit 20 tasks** **20 cores used** **(hh:mm:ss)**
1 Plume	00:04:06:16	00:00:10:36	00: 00:06:20
2 Head	00:08:48:39	00:00:17:42	00:00:10:56
3 Neck	00:03:24:38	00:00:07:17	00:00:04:18
4 Shoulders	00:22:11:55	00:00:47:37	00:00:27:48
5 Trunk	01:03:42:02	00:00:57:36	00:00:33:28
6 Waist	02:09:19:34	00:01:54:03	00:01:06:49
7 Clothing	02:09:12:19	00:01:56:25	00:01:07:40
8 Legs A	02:22:38:09	00:02:33:10	00:01:27:12
9 Legs B	03:13:54:56	00:04:08:50	00:02:28:45
10 Feet	04:23:48:08	00:03:55:17	00:02:20:40
11 Arm right	00:17:20:51	00:00:46:54	00:00:27:44
12 Arm left	00:21:59:42	00:00:44:18	00:00:26:15
TOTAL:	20:15:24:18	00:18:19:44	00:10:47:55
SRF (Unibo):	1.00	27.03	45.88
SRF (HPC):	0.04	1.00	01.70

Table 8. Reconstruction Times for all systems for each section.

5. Conclusions

The Department of Physics at the University of Bologna now has a system that provides significantly faster tomographic analysis than was previously available, thus making it possible to conduct new, innovative studies. The university has experienced a significant increase in speed since its move to Windows HPC Server 2008. We get results on the cluster that are faster than our previous setup by a factor of up to 75, and for the analysis of the Kongo Rikishi statue, for instance, we've reduced image processing time from 20 days to just 6 hours. Because the university can carry out calculations quickly, it will be able to conduct real-time analysis, which is particularly important in medical research. The possibility of real-time analysis will resolve the problems connected with small movements of patients during CT scans. For the university, using Windows HPC Server 2008 has opened up new possibilities in the fields of cultural and medical research. Its X-Ray Imaging Group is currently the only research group in the world capable of carrying out tomographic analyses on large objects [5].

System	bit	cores	Tasks	Total time	Sec/slice	SRF Unibo	SRF HPC
Unibo	32	1	1	20:15:24:18	226.98	1	- - -
HPC	64	20	800	00:17:15:43	7.89	28.76	1
E4	64	20	240	00:10:47:55	4.94	45.97	1.60
E4	64	24	800	00:08:45:00	4.00	56.74	1.97
E4	64	32	800	00:06:36:37	3.02	75.10	2.61

Table 9. All times and seconds per slice for the three systems.

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Index