Ultra-Fast Hierarchical Backprojection for Micro-CT Reconstruction

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***Abstract*–This paper introduces a new version of a fast and accurate $O(N^3 \log N)$ reconstruction algorithm for cone-beam CT with a circular source trajectory. This is the first report on the performance of this algorithm with high-resolution large-matrix Micro-CT data. We determined that a software implementation of the FHBP algorithm on off-the-shelf workstations can provide speedups by an order of magnitude or more in Micro-CT reconstruction with no perceptible loss of image quality as compared to state-of-the-art commercial software implementations of conventional reconstruction. This is especially important for Micro-CT reconstructions, where maximum image size can be as large as 8Kx8K pixels per slice and reconstruction of such image volumes can span days. Owing to its algorithmic acceleration, the FHBP-based code achieves the performance of a cluster of computers on a single PC, and could provide even faster reconstruction rates if operating on the entire cluster.**

I. Introduction

CIRCULAR cone beam (CCB) acquisition involves an x-ray source revolving around an object in a circular trajectory, with projections collected on a flat detector plane (Fig 1). The standard reconstruction algorithm is the Feldkamp-Davies- Kress (FDK) algorithm, where each projection is weighted and filtered, then backprojected onto the image volume. This 3D backprojection is an $O(N^4)$ operation. For Micro-CT scans, which produce very fine, high resolution volumes, cross-section sizes range from 1Kx1K to 8Kx8K. Therefore the $O(N^4)$ complexity can result in extremely long run times. Typically these reconstructions are performed in software, so for even moderately sized images, a cluster of for FHBP networked computers is used to make the reconstruction times tolerable. Fast reconstruction algorithms reduce the complexity of the backprojection to $O(N^3 \log N)$, which can result in considerable speedups, especially as the image size increases.

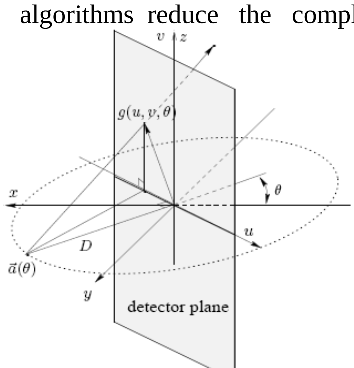

Fig.1. Circular Cone Beam Acquisition Geometry

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Our goal was to develop a complete ultra-fast Micro-CT software reconstruction engine for an off-the-shelf workstation, using FHBP algorithms and including all necessary preprocessing steps. The challenges in this design include

- Huge data set sizes (10’s of GB to 100’s of GB)
- Wide cone angles
- Mapping a complex FHBP algorithm to an efficient software implementation
- Maximizing speedup while preserving image quality

II. Ultra-Fast Backprojection

The reconstruction algorithm used here is based on fast hierarchical backprojection (FHBP). FHBP is a divide-and-conquer algorithm, where the volume to be reconstructed is successively subdivided into smaller, non-overlapping subvolumes. Owing to sampling conditions of CCB reconstruction [1], the projection data can be decimated for each subregion, reducing the amount of data required to reconstruct the region while maintaining image quality. The procedure for decimating the projection data involves shifting projections followed by angular decimation [2].

Other fast algorithms, such as those based on Fourier reconstruction [3] or multilevel methods [4], were originally designed for the parallel-beam geometry and have difficulties in extending to cone beam geometries. Such methods extend only approximately, resulting in only modest speedups if image quality is to be maintained. Alternately, a rebinning operation can convert the data to the parallel beam geometry so that these algorithms can be more readily applied. However, this rebinning also introduces a significant computational overhead, so that the rebinning itself does not introduce artifacts in the reconstructed image. FHBP is the only fast algorithm known to operate on the cone beam data natively, providing a significant speedup while maintaining image quality.

A. *Fast Hierarchical Backprojection*

The FHBP algorithm for CCB trajectories [2] operate using two main concepts. The *first concept*, is that the number of projections needed to accurately reconstruct a bandlimited subvolume at the center of the source of rotation, is proportional to the size of the subvolume. It follows that for the reconstruction of a half-size subvolume, the projection data set can be angularly decimated by a factor of 2, from P to P/2 projections without any loss in reconstructed image quality. This property is extended to apply to subregions located at any position in the image. First, projections of the subvolume are "centered" by shifting in the projection plane to the position of the footprint of the center of the source rotation, as shown in Fig. 2. This reduces their angular bandwidth, so that centered projections may be decimated without information loss. The decimated projections are then shifted back to their correct positions. The combined operation of centering, angular decimation, and de-centering is denoted by the acronym SDSB (Shift-Decimate-Shift Back), summarized in Fig. 3. Applying the SDSB operation results in a factor of 2 savings in backprojection of that subvolume.

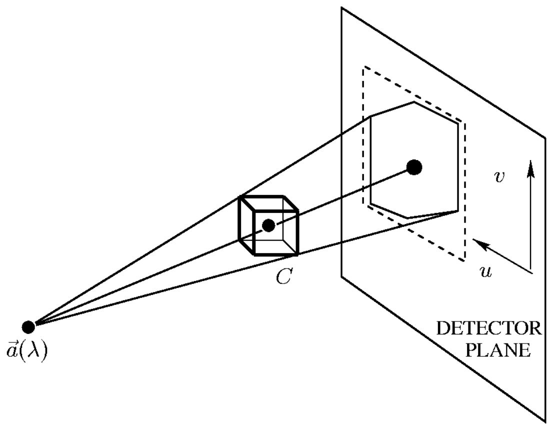

Fig. 2. "Centering" Shift for FHBP

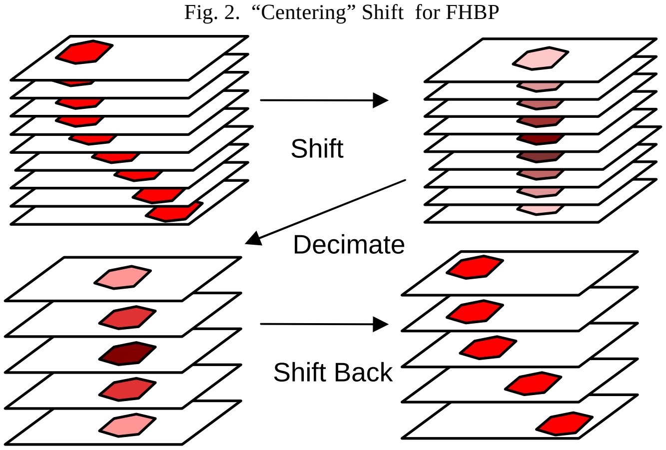

Fig. 3. Shift-Decimate-Shift Back Operation

The *second concept* is "divide and conquer" in which the reconstructed volume is successively divided into smaller non-overlapping volumes, with the SDSB operation applied to each subvolume. At every stage in this hierarchical decomposition, the number of projections is reduced by another factor of 2. Applying it logN times yields N^3 single voxel subvolumes, which require backprojection of P/N projections each, for a total of $O(N^2P)$ work in the last stage. It turns out that the work for the SDSB operations in each step is also $O(N^2P)$, yielding a total cost of $O(N^3 \log N)$ for the hierarchical algorithm, since P = O(N) for good image quality.

Previous work on FHBP for CCB [2] divided the volume into pillars in a cylindrical geometry (i.e., no decomposition in Z). For the geometries considered here, it was found that a full 3D decomposition was required for maintaining image quality. The cause is the much taller detector used in Micro-CT compared to the medical CT scenario, for which the original CCB FHBP algorithm had been developed. This recursive 3D decomposition, illustrated in Fig. 4, is similar to the decomposition we proposed in our algorithm for the helical cone-beam geometry [5].

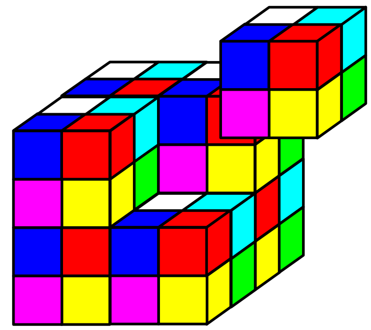

Fig. 4. Recursive Decomposition

B. *Full Reconstruction Algorithm*

In addition to the algorithmically accelerated backprojection, we integrated the necessary preprocessing steps, such as beam-hardening correction, ring artifact removal, and filtering, so that the code can be interfaced directly and tested with Micro-CT projection data. We implemented and adapted algorithms for the various corrections using techniques described in the literature. The only significant pre-processing computation is for the filtering step because it scales as $O(N^3 \log N)$, i.e., the same order as the hierarchical backprojection. These preprocessing steps have not been extensively optimized. However, the preprocessing step also includes significant shuffling of the data, and memory-disk transfers. Our development therefore addressed efficient ways to combine the preprocessing with the architectural hierarchy of the fast backprojection, to reduce data shuffling.

III. Implementation and Testing

The FHBP algorithm was implemented on a Xeon CPU, using the SSE vector instructions Currently our software implementation has only a single computational thread, as compared to commercial reconstruction packages that support multi-CPU and multi-node platforms. For comparison purposes we scale all reconstruction code described here to the single processor case.

For image quality and speed evaluations we collaborated with two academic research groups that operate Micro-CT scanners from different manufacturers. These groups provided data from their experiments, and evaluations of the performance of the FHBP reconstruction algorithm. In addition, we performed several quantitative image quality assessments in-house, as shown in Figs 4,5.

To evaluate the acceleration provided by the new prototype software, we compared it to two commercial systems: (1) the *Nrecon* software, from SkyScan, one of the major manufacturers of Micro-CT scanners and (2) GE reconstruction software supplied with their 'eXplore Locus SP' Micro-CT scanner. The test system was a Xeon workstation running at 3.0 GHz, with 2 GB of RAM and a 2 disk RAID for improved disk I/O of large projection and image volume data. Speed measurements were preformed by timing the developed software on the target platform. We had the latest release of the SkyScan reconstruction software, Nrecon, available to us, and were able to run it on the same platform, for timing comparisons. The GE reconstruction software was run by our collaborators at the University of Michigan on their system – a 2 node cluster made up of two workstations, each with two 3.0 GHz Xeon processors. Hence, their system has a total of 4 active processors. The parameters of each of the Michigan Xeon processors are very similar to our own, so to translate run times reported by the Michigan group for the GE software to equivalent run-times on a single Xeon processor, we multiplied the reported times by 4.

IV. Results

We present results from two sets of Micro-CT data provided to us by our collaborators. To validate image quality, the image volumes were reconstructed with the FHBP software along with the corresponding conventional commercial reconstruction software for use as a reference. The reconstruction results were provided to the two respective groups for comparison with the reference results. Each group reported negligible difference between the two reconstructions. Examples of these reconstructed volumes are shown in Fig 7.

Table 1 summarizes the reconstruction rates (expressed in slices per second) for the FHBP reconstruction software compared to commercial software packages operating on the same datasets. All runtimes are normalized by the number of processors being used. The first evaluation examined 1Kx1Kx512 voxel volumes provided by the University of Michigan group. The GE reconstruction software combines the preprocessing steps of weighting and filtering along with backprojection, which prevented us from getting precise numbers on the time spent just doing backprojection. However, when including those same preprocessing steps in the FHBP algorithm, the FHBP reconstruction provides a 30x speedup over the GE software.

The data sets from the University of Illinois group were sufficient for image volumes with 2Kx2K cross sections. We compared our speed to the SkyScan Nrecon commercial software package, which does report separate preprocessing and backprojection times. Here the FHBP software provides a 9x speedup. This dataset proved more challenging to attain good image quality, due to the low number of projections (Note that the number of projections is half that of the 1Kx1K Michigan data, even though it is double the resolution – generally the number of projections should scale linearly with image size to maintain image quality). Importantly, for the complete reconstruction system including pre-processing, we demonstrated 8X speedup in the reconstruction of a 2K x 2K x 256 voxel volume compared to Nrecon.

V. Conclusion

The results reported here demonstrate the substantial speedup of the FHBP algorithm when integrated into a full reconstruction engine, even when compared to commercially available software packages. The algorithmic reduction of FHBP shows the potential for even greater gains at higher resolutions. The positive results of the image quality evaluations indicate the likelihood of end user acceptance of the reconstruction algorithm. In addition, a fast backprojection engine is a crucial first step in development of advanced reconstruction techniques using iterative algorithms.

Acknowledgment

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References

[1] J. Brokish and Y. Bresler, "Sampling Requirements for Circular Cone Beam Tomography," 2006 *IEEE Image Processing Conf., Nuclear Science Symposium Conference Record* pp. 2882-2884.

[2] S. Xiao, Y. Bresler, and D. Munson, "Fast Feldkamp Algorithm for Cone-Beam Tomographic Reconstruction," in *Proc. Int. Conf. Image Process.* Sept. 2003.

[3] Y. O'Connor and J. Fessler, J.A "Fourier-based forward and back-projectors in iterative fan-beam tomographic image reconstruction", *IEEE Trans. Med. Imaging*, 2006.

[4] A. Brandt, J. Mann, et al "Fast and Accurate Multilevel Inversion of the Radon Transform," *SIAM J. Appl. Math*, 1999

[5] Y. Bresler and J. Brokish, "A Hierarchical Algorithm for Fast Backprojection in Helical Cone-Beam Tomography," in *Proc. 2nd Int. Symp. Biomed. Imaging*, 2004

		Slices per second		
Recon Parameters	**Preprocessing?**	**Conventional**	**FHBP**	**Speedup**
1Kx1K Slices from P=720 projections	No	0.05* (GE)	1.80	36x*
1Kx1K Slices from P = 720 projections	Yes	0.05 (GE)	1.48	30x
2Kx2K Slices from P=481 projections	No	0.10 (Nrecon)	0.87	9x
2Kx2K Slices from P=481 projections	Yes	0.08 (Nrecon)	0.69	8x
*Could not determine Backprojection Only time for conventional code in this case – preprocessing time is included				

Table 1. Timing Comparison Conventional FBP vs FHBP

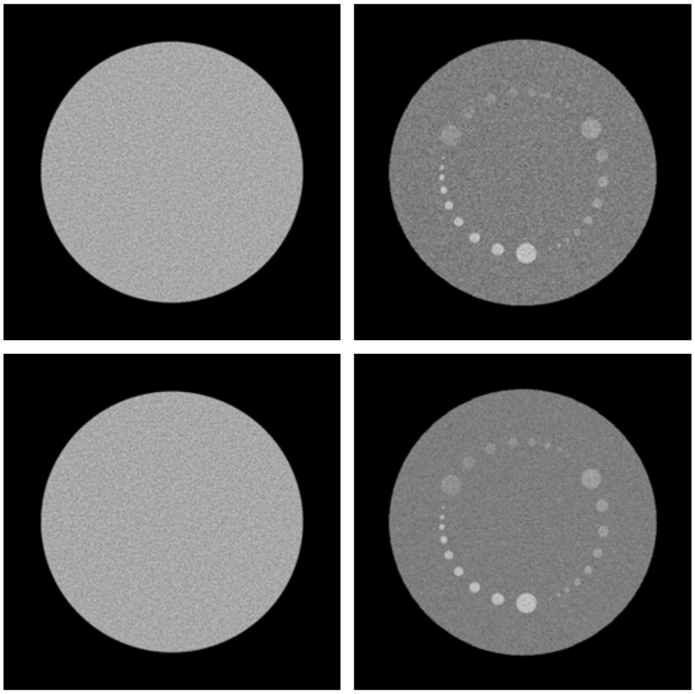

Fig. 5. Quantitative Test Suite comparing Conventional FBP (top row) with Hierarchical Backprojection (bottom row). Tests included CT Number Uniformity and Noise (left column) and Low Contrast Detectability (right column).

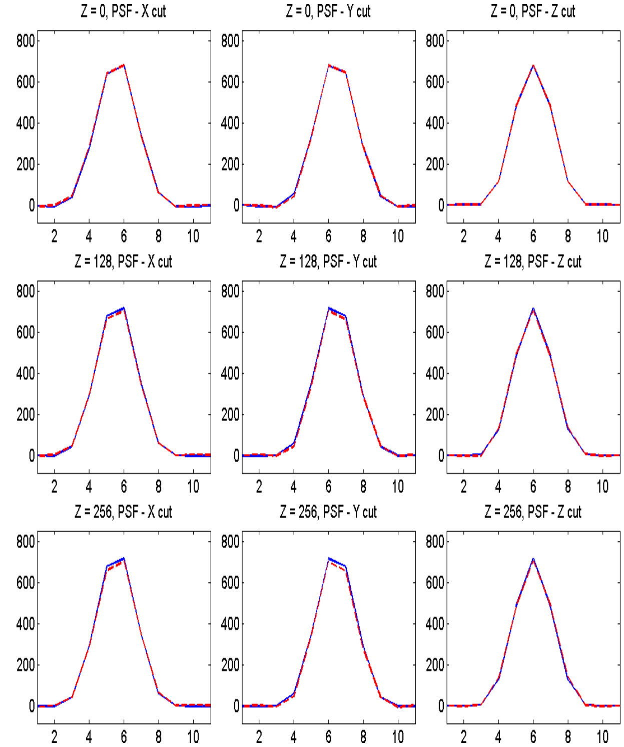

Fig 6. PSF Test for a test point target arrangement. Conventional FBP is blue, solid, and Hierarchical FHBP is red, dashed.

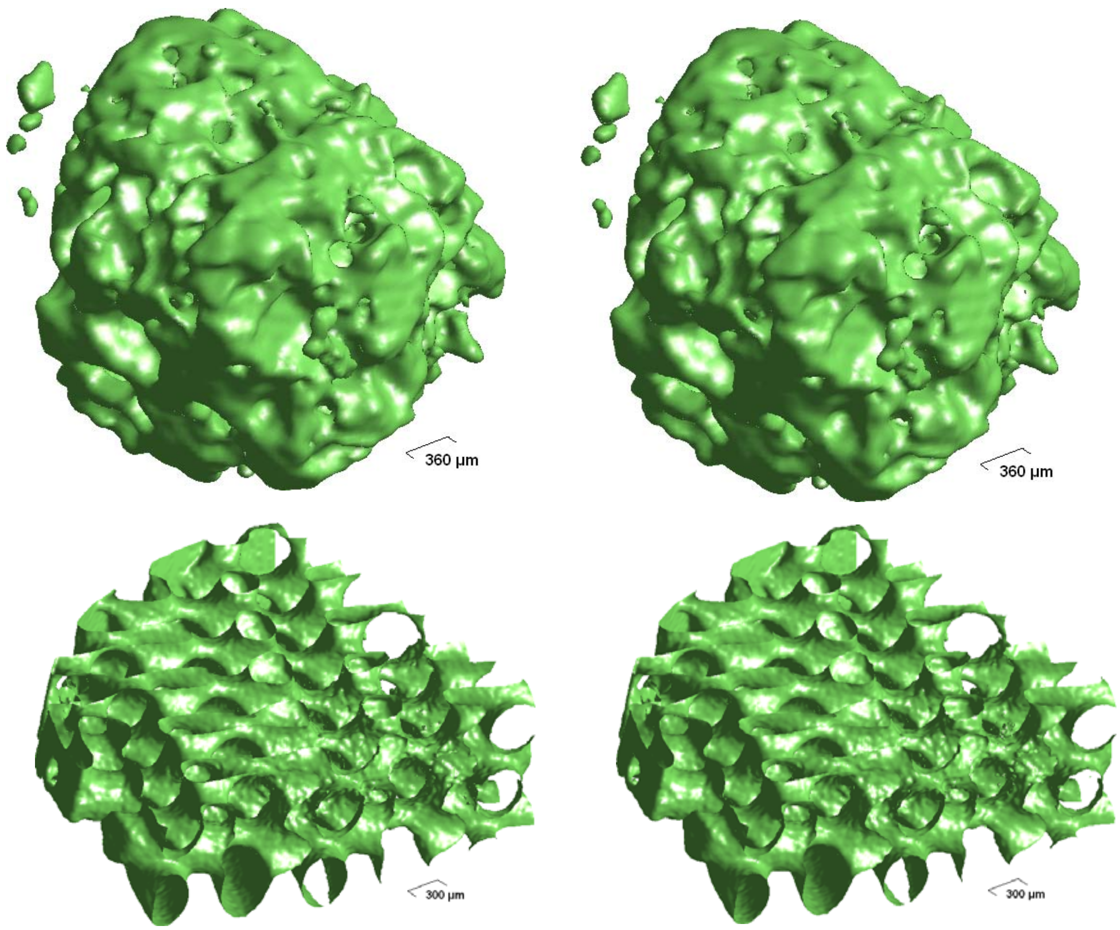

Fig. 7. Qualitative Test Suite comparing Conventional FBP (left column) with Hierarchical Backprojection (right column).