Homemade computed tomography setup with FDK reconstruction software

A S Kussainov 1,2 and N O Saduev 1,2
1Physics and Technology Department, al-Farabi Kazakh National University, 71, al-Farabi Ave, Almaty, 050040, Republic of Kazakhstan
2National Nanotechnology Laboratory of Open Type, 71, al-Farabi Ave, Almaty, 050040, Republic of Kazakhstan
E-mail: arman.kussainov@gmail.com

Abstract. X-ray source, detector and rotation stage as the sample holder were used to built the hardware part of the homemade CBCT scanner. The full scale numerical simulation of the CBCT experiment was modified to complete the scanner. This C/C++ software package is capable to process an arbitrary CT experimental or synthesized data for 3D reconstruction using the FDK method. The high degree of the package’s flexibility allows different CBCT recording and reconstruction geometries with different source and detector positions and their spatial trajectory. The classical computed tomography arrangement, when the gantry, rotating around the sample, is loaded with the opposed sources and detectors, was replaced by the rotating sample and fixed source and detector. Mismatches between these two schemes in reconstruction procedure such as misplacement of the rotation axis from the expected location and other misalignments are compensated by introducing the corresponding variables in the reconstruction software.

1. Introduction
CT is an indispensable tool in health care, non-destructive sample analysis and other research projects. The simple set of X-ray projections taken from a limited number of angles or viewpoints could be turned into a high resolution 3D analytical tool with a low maintenance cost. The crucial analytical part of this tool is a reconstruction software, capable of creating the 3D image from the set of these projections. The main reconstruction principles are best interpreted using the Fourier slice theorem, see [1] and [2], and have been adapted for use on the modern hardware and software.

High resolution CBCT numerical simulations are somewhat computationally intensive and in general require multithreading techniques. For the 72 voxels per cm of spatial resolution, one can put a rough estimate on the computational efforts to optically trace (cast a shadow of) a sample to the single 3072 × 2560 X-ray projection. For the typical distance from source to detector equals 15000 voxels and with 100 entries, from 1 to 100 KeV, of the X-ray source spectrum, these contributes up to the 12 × 10^{12} of non-trivial ray tracing operation for building a single digital projection. Multiple optimizations for the standalone backprojection part of the simulation software allow us to drastically increase the reconstruction speed though we still need the hardware acceleration to provide the performance and interactive environment for the operator.
Conventionally, the CPU multithreading holds its leading positions in CBCT acceleration techniques due to the simplicity of the coding, straightforward volume compartmentalization and still growing availability of the multicore CPUs but it is gradually replaced by the parallel computations on GPUs [3] and even on cell broadband engine architecture chips [4].

In this paper we demonstrate the combination of the homemade X-ray projections acquisition setup with our reconstruction software and CPU based acceleration to produce a working CBCT scanner solution.

2. Methods
The most frequently used and implemented backprojection method in CBCT is the FDK algorithm and its variations. In this paper we are using the basic X-ray tomography FDK and not comparing it to the other not less effective reconstruction methods like ART/SART [5] and to different data acquisition techniques like ultrasound, microwave, positron-electron emission tomography etc utilizing the same or related image reconstruction principles.

To compliment the homemade X-ray projections acquisition setup with a 3D data FDK reconstruction software we have maintained and adapted our previously written C/C++ package simulating a full scale numerical CBCT experiment [6]. This package is designed first to synthesize the arbitrary shaped and structured high resolution three dimensional radiological phantom from the user’s input about the desired structure and material of the phantom. Then the phantom is irradiated to produce the successive series of the cone beam projections taken with different values of rotation angle of the source and detector around the phantom. Various testing chamber’s conditions and configurations including the mammography case have been implemented by enabling the flexible recording geometry in the code’s mathematical apparatus. At last, these synthesized projections are used to reconstruct, slice by slice, the internal structure of the phantom by backprojecting with FDK algorithm.

The close match between these simulated X-ray projections and real data acquisition setup allows us to use the reconstruction part of the package to compliment our experiment up to the complete CBCT scanner solution.

2.1. Reconstruction Algorithm
For a single 2D fan rotating in the central plane, the reconstruction procedure for a \( f(r, \phi) \), or matching it \( f(t, s) \) slice shown as a square rectangle on Figure 1(a), is given by the next equation (1)

\[
f(r, \phi) = \int_0^{2\pi} \frac{1}{U^2} \int_{-\infty}^{\infty} P_\beta(p) g(p'- p) \frac{D}{\sqrt{D^2 + p^2}} dpd\beta, \tag{1}
\]

where \( D \) is the distance from the source \( S \) to the axis of rotation perpendicular to the \( XY \) plane and marked with point \( O \), \( p \) is the variable used to measure the distance from the central point \( O \) on the rotation axis to the point \( O' \) produced by the crossing of the backprojected ray \( P'S \) with the \( t \) axis, see [1]. Axis \( t \), along which the variable \( p \) is taken, is parallel to the detectors line and considered to contain the projections values referenced as the \( P_\beta(p) \). These values are projected from the origin of the \( P'S \) ray. Here \( g(p) = \frac{1}{2} h(p) \) and \( h(p) \) is the inverse Fourier transform of \( H(\omega) \). That is

\[
H(\omega) = |\omega| b_\omega(\omega),
\]

\[
b_\omega(\omega) = \begin{cases} 
1, & \text{if } |\omega| < W \\
0, & \text{if } |\omega| \geq W,
\end{cases} \tag{2}
\]
where $W$ defines the window’s size for the high-pass filter $H(\omega)$ in the Fourier space of the spatial frequencies $\omega$ and

$$U(r, \phi, \beta) = \frac{D - s}{D}.$$  \hfill (3)

\textbf{Figure 1.} Backprojecting algorithm’s geometry for the FDK method, where (a) is a 2D case and (b) is a 3D case.

Backprojecting algorithm for the oblique fan $f(t', s')$ tilted from the central plane, see Figure 1(b), is built from this basic case by applying the coordinates transform and rotation formulas to produce a slightly different expression

$$f(t, s) = \frac{1}{2} \int_0^{2\pi} \int_{-\infty}^{\infty} R_\beta(p, \varsigma) \cdot h \left( \frac{Dt}{D - s} - p \right) \frac{D}{\sqrt{D^2 + \varsigma^2 + p^2}} dp d\beta,$$  \hfill (4)

For convenience, we have immediately switched back to the $(t, s)$ coordinates of the central fan related to the $(t', s')$ by the set of the equations

$$t' = t, \quad \frac{s'}{\sqrt{D^2 + \varsigma^2}} = \frac{s}{D}, \quad \frac{\varsigma}{D} = \frac{z}{D - s}.$$  \hfill (5)

In addition to the already known variables, $\varsigma$ stands for the elevation of the $t'$ axis above the central plane and $s$ is measured from the point $O$ along the central ray on both pictures (a) and (b) in Figure 1. Rotated coordinates $(t, s)$ are related to the $(r, \phi)$ coordinates by the following expressions

$$t = x \cdot \cos(\beta) + y \cdot \sin(\beta), \quad s = -x \cdot \sin(\beta) + y \cdot \cos(\beta)$$

$$x = r \cdot \cos(\phi), \quad y = r \cdot \sin(\phi).$$  \hfill (6)

The $f(x, y, z)$ slices of different thickness and spatial orientation could be assembled into a 3D structure in the same software package or by a separate one, Matlab in our case.
2.2. Software Customization

When implementing the equations (1) through (5), the multiple optimization, filtering and multithreading techniques, such as OpenMP directives, have been used to increase the performance [6]. At backprojection stage we basically parallelize the two nested loops running over the reconstructed \{ABCD\} slice’s two dimensions, see Figure 2 (a). One can see, that from each projection we need to backproject only the shadow of a reconstructed slice, see polygons \{A_1B_1C_1D_1\} and \{A_2B_2C_2D_2\}, not the whole projection, which greatly increases the performance. Without a further optimization the reconstruction of a single 1024 × 1024 slice from the set of 116 projections, taken with 2 degrees step, takes about several seconds, see Figure 3. For numerical simulations and data reconstruction we have used a desktop PC with the 8-core Intel(R) Core(TM) i7 – 4790K CPU @ 4.00GHz with excessive 32 Gb RAM.

![Software Customization Diagram](image)

**Figure 2.** (a) Individual slices \{A_1B_1C_1D_1\} and \{A_2B_2C_2D_2\} shadows’ contribution to the backprojection on the plane \{ABCD\} procedure, (b) Sample’s rotation and nutation. The X-ray source is not shown.

The primary feature of the commercial CT scanner in a hospital, besides the power deposition and radiation exposure limits, is that a great deal of attention is paid to keep the subject, often human, probably sick and immobilized, undisturbed. For this purpose, the X-ray sources and detectors are assembled into the ring moving around a subject with the Z axis corresponding to this rotation. This basic recording scheme for the computer assisted tomography was discussed above.

In the lab conditions, on the contrary, one is keeping the X-ray source and detector panels securely fixed and immobile. The objects of study are either moved on the conveyer belt or rotated by means of a special sample holder around some \(Z'\) axis placed between X-ray source and detector panel, see Figure 2(b).

If the fixed, with respect to the rotation of the sample, \(Z'\) axis is aligned with the meant-to-be rotation axis \(Z\) for the source-detector pair one can easily switch back and fourth between the rotating sample and the rotating source and detector system of coordinates, see Figure 2(b) [7]. Math stays the same and only the rotation angle \(\beta\) changes its sign. Our software package is designed to accept the component of the displacement vector for the misaligned coordinate systems XYZ and X’Y’Z’ in the numerical version of the Eq.1. It is hard to know the values of this displacement vector beforehand and it is done by an operator while working with our software package.

The FOV shift caused by this undesirable coordinates misalignment is compensated at the final stage of the reconstruction, by correcting the \(x\) and \(y\) values assumed to be present in
Figure 3. (a) Typical projection, (b) Coronal, (c) Sagittal and (d) Axial slices of the tubular sample under investigation.
the left, \( f(r, \phi) \) part of the Eq.1. Software package also provides the means to choose the slice thickness, its orientation and image filtering techniques.

2.3. Hardware, Sample Description and Recording Conditions
We have used the G-297, rotating anode X-Ray tube from Varex Imaging. The G-297 is a 102 mm, 150 kVtube with rotating anode insert and 445 kJ maximum anode heat content. PaxScan 4336W v4 flat panel detector from Varex Imaging with amorphous silicon TFT/PIN diode technology was used for image registration. These hardware is originally designed and used for the airport security scanners as well as for the heavy duty general radiographic, cineradiographic and fluoro/spotfilm procedures etc.

The set of tubes and air-filter-like material were assembled into a cylinder sample, see projections and reconstruction images on Figures 3 and 4. The sample contains arrangement of the tubes from 5 mm down to capillary sized. The overall height of the assembly is 230 mm and its diameter is 50 mm. The material of the tubes is acrylic and they glued together with the epoxy resin. The air-filter like layer is made from cellulose.

The projections were taken with the fixed X-ray source and detector separated by the distance of 208 cm. The sample was placed at the top of the optical grade rotating stage between the source and detector, 139 cm away from the source. The source, detector and sample were placed in the same plane for the sample’s shadow to fit the detector. After each exposition our technician manually rotated the sample using the knobs on the rotation stage. We did our best to manually align the axis \( Z' \) of the sample rotation with the axis \( Z \) of the ideal CBCT scanner but still were off by few millimeters.

The operator is able to supply the complete set of these parameters in the form of the text file into the reconstruction software or input them manually to the code before the C/C++ package compilation stage.

3. Results
Figure 3 (a) shows a typical single projection of the sample, treated for the brightness and contrast levels for printing purposes only. The next three pictures, see Figure 3 (b) - (c), are the coronal, sagittal and axial slices reconstructed from the whole set of these 116 projections. The later are taken with 0 to 230 degree rotation angle values with 2 degrees step.

As expected, for the divergent cone beam and the limited number of projections, the best clear slice images are obtained in the central cardinal planes. No additional postprocessing, noise removal or edge sharpening have being introduced at this stage and images are still showing quite a decent quality.

The next group of pictures, see Figure 4 (a), represents a 3D reconstruction of the whole sample, rotated 90 degrees clock-wise to fit the page’s width, and the set of slices of different thickness and location, see Figure 4 (b)-(i),taken one by one from the bottom of the sample, all the way up to its top, to show the inner structure of the sample. For the ease and speed of implementation the 3D reconstruction was made in a separate Matlab package. All the structures are clearly visible and freed from the motion artifacts expected in our case from the misplaced axis of rotation, see Figure 2(b). The axes misalignment vector component values were introduced into the code after the visual control of the reconstructed slice image.

4. Conclusions
The cost of a commercially available scanner is up to several hundreds of thousands dollars worth of equipment and software and that is not including the maintenance cost. We have demonstrated that with the minimal configuration efforts invested into the hardware such as X-ray source, detector array and sample holder, a research group could built a reliable tool for studying the structure of the different X-ray transparent samples. Spatial resolution of this tool
Figure 4. 3D reconstruction of the sample and it is internal structure. Slices of different thickness and locations are shown in a successive order left-to-right and top-to-bottom. Sample and slices dimensions and sizes are given in voxels. There are 72 voxels per centimeter in this particular reconstruction.
is in sub-millimeter range with good contrast and time resolution for the transient processes. The elements of setup could be salvaged or borrowed from the various projects utilizing X-ray sources and registration techniques.

Of equal importance becomes the software for data preprocessing and reconstruction. At this stage the qualified programmers personnel could be able to use different and freely available hardware acceleration tools including CPU and GPU multithreading to write a software package of their own. Once developed, this software could be later used for the similar reconstruction principle setups where the series of transmission or reflection images are taken from a sample from the multiple points to reveal the internal or external structure.

The cone beam CT arrangement allows to do even the microscopy experiments with magnification caused by the divergence of X-ray beam and high resolution detectors.

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