A platform for Image Reconstruction in X-ray Imaging: Medical Applications using CBCT and DTS algorithms

Invited Article

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Abstract

This paper presents the architecture of a software platform implemented in C++, for the purpose of testing and evaluation of reconstruction algorithms in X-ray imaging. The fundamental elements of the platform are classes, tightened together in a logical hierarchy. Real world objects as an X-ray source or a flat detector can be defined and implemented as instances of corresponding classes. Various operations (e.g. 3D transformations, loading, saving, filtering of images, creation of planar or curved objects of various dimensions) have been incorporated in the software tool as class methods, as well. The user can easily set up any arrangement of the imaging chain objects in 3D space and experiment with many different trajectories and configurations. Selected 3D volume reconstructions using simulated data acquired in specific scanning trajectories are used as a demonstration of the tool. The platform is considered as a basic tool for future investigations of new reconstruction methods in combination with various scanning configurations.

Keywords: Computed Tomography, Digital Tomosynthesis, CBCT, image reconstruction, class library.

1 Introduction

Virtual instrumentation has become a valuable tool for testing or evaluating different approaches, methods, and techniques in any research field. In the field of Medical Imaging this is especially valid for the radiography, nuclear imaging, computed tomography, etc., where due to the hazardous nature of the radiation and the limited access to instrumentation, organizing experiments is often difficult. There exist software packages [1-6], which can be used for simulation of X-ray images. For producing series of realistic projections these packages usually assume known, well-studied scanning trajectories, and the development or testing of new approaches is usually related to a significant additional programming work.

The idea to develop a dedicated library to be used in simulations in the field of X-ray imaging originates in the past [7]. Since its earlier implementation showed some drawbacks, the authors have started to develop a new such library – RTCL: Reconstruction Techniques Class Library [12] based on the experience acquired in the field of X-ray imaging algorithms and taking into account the much larger variety of possible applications. During the creation of the library two main application aspects were considered. Firstly, in many cases, known image reconstruction algorithms need to be applied over various projection data. Therefore, the possibility for fast development of such type of applications has been targeted. Secondly, it would be valuable to possess a tool for convenient programming and testing of new reconstruction techniques, using modified or completely new projection acquisition trajectories, etc. and this has been the main driving force to create the RTCL.

This paper describes the current structure of the RTCL library and the way it can be used for developing software applications within the field of the X-ray Computed Tomography (CT). The library is now the core component of an ambitious software application – the Platform for Image Reconstruction in X-ray Imaging (PIRXI). An initial version of the platform has already been developed and is currently used in research projects of the team. The present paper also describes key points in the development of PIRXI and the adopted approach of defining tasks, accessing projection data from different sources. Finally, the paper includes examples of reconstructed images with the help of PIRXI, from simulated data used in medical imaging, after applying Cone-beam CT (CBCT) or Digital Tomosynthesis (DTS) reconstruction algorithms.

2 Materials & Methods

2.1 The RTCL

In RTCL, with respect to its predecessor, assignment, inheritance of geometrical and functional properties, and the use of all library components have been implemented in a different and more practical way. An overview of the different groups of classes and relations is represented by the simplified diagram in Figure 1. An object-oriented programming approach, which perfectly complies with the object-oriented composition and functioning of the CT imaging systems, has been followed.

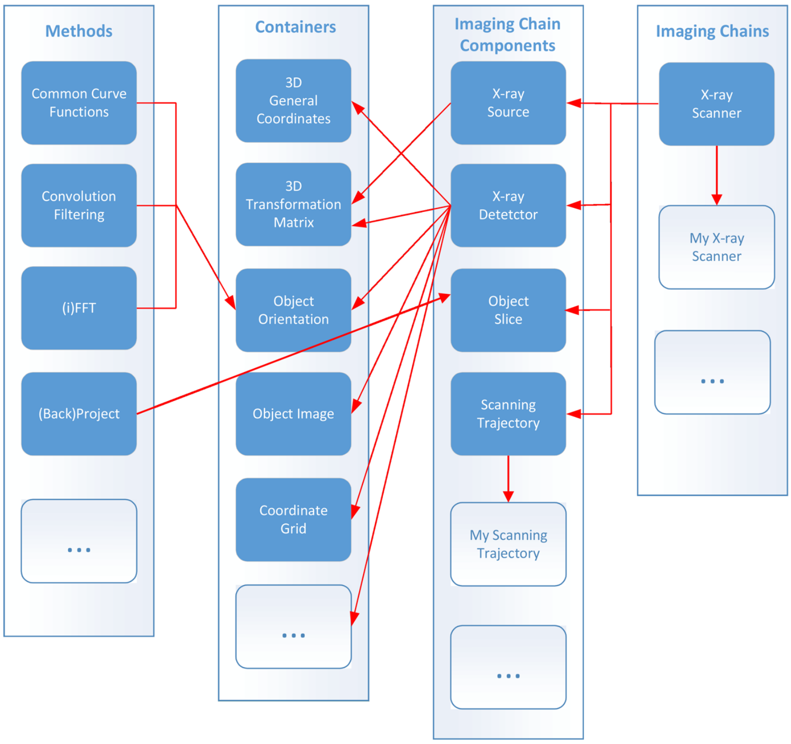

Figure 1. Basic components of the RTCL library

Components in a real CT imaging chain usually include X-ray source(s), X-ray detector(s), mechanical construction able to move the source-detector pair(s) along a specific trajectory, data processing unit(s), dedicated image reconstruction processor and object motion-correction techniques. RTCL provides the programmer with software equivalents of those components, allowing intuitively and easily to repeat and simulate any imaging setup and eventually use the available projection images to reconstruct tomograms at arbitrary orientations. RTCL offers different types of classes, which combine content and inherit properties in a hierarchical sequence. The Containers group comprises classes for handling 2D/3D coordinates (of pixels, voxels, vectors, etc.) either locally on a surface (e.g. detector plane) or globally in the 3D space. Grid classes carry analytical description of different surfaces and contain arrays of the coordinates of their nodes. The latter can belong to a flat surface, thus are equidistantly distributed over a plane, or they can belong to a curved (cylindrical, spherical) surface, therefore following a different description. Sets of Euler angles describe the orientation of objects in space. Images are separate containers for different types of image data. The Methods group of classes provides mostly functions to facilitate handling and processing projection or reconstruction data. It includes common 1D/2D functions (e.g. signal windows, filter kernels, filter responses), FFT/IFFT routines, convolution/filtering routines, for image processing in the frequency and the spatial domain. Projection/backprojection routines are also implemented in order to help in the validation or development of analytical reconstruction methods or in the production of experimental projection images. Specific classes form the Imaging Chain Components group. Detectors represent the variety of image sensors used in the CT imaging, fluoroscopic or any other direct way of imaging. Within a 2D detector, pixels are uniquely identified by their indices or by their local or global coordinates. It is always possible to convert any type of coordinates to any other type, using the a priori information for the imaging system. Trajectory classes incorporate geometry and motion of different setups of source-detector pairs and simplify their positioning in space. Examples include circular isocentric trajectory, spiral/helical, partial isocentric along a limited arc, linear, etc. Slices are utilized in the representation of tomographic images or 3D volumes, while the X-ray source class, for example, describes a point source in terms of its coordinates, focal spot size, energy, field distribution, etc. The Imaging Chains group is intended to contain functional aggregations (e.g. scanners, C-arms, etc.) of the above classes. The last two groups are considered quite open (from the user's/developer's aspect) and any new development (e.g. trajectories, geometrical configurations) can be added.

Figure 2 helps to illustrate the example definition of a simple CArm scanner class. As it is shown, the class is defined initially by inheriting most of the functionality from a ready abstract class, the BaseXrayScanner. This parent class contains abstract components like a base-source, a base-detector, a base-trajectory as well as virtual methods (e.g the function that is expected to implement the relevant movement – *moveTo(...)*) that the children classes should override accordingly. The constructor of the derived CArm class is written in a forward manner, as it is shown on the right. The input arguments in the definition of the constructor are already specific for the derived class e.g. the source to isocenter distance (SID), the source to detector distance (SDD), the number of nodes along the principal axes of the detector as well as the size of its pixels. In the implementation, these arguments can be used to create and retrieve specific components, like an XrayPointSource, and a FlatXrayDetector, where the S and D denote pointers to abstract equivalents of these components.

The rotation of the gantry is translated into motion of the source-detector pair. The rules for that could be provided by the Circular Trajectory Class. With the help of an overloaded function (e.g *moveTo(...)* in Figure 2) the source-detector pair is instructed to move along a circular arc synchronously, defined exactly by the Circular Trajectory Class. The backprojection operation is performed with the help of a universal projector/backprojector function. The arguments of this function include a Projection Set Description object, which fully describes the acquisition and geometrical setup of an imaging scenario and a Slice object on which the backprojection process will be performed. The compactness of the code proves the robust implementation of the initial idea of RTCL.

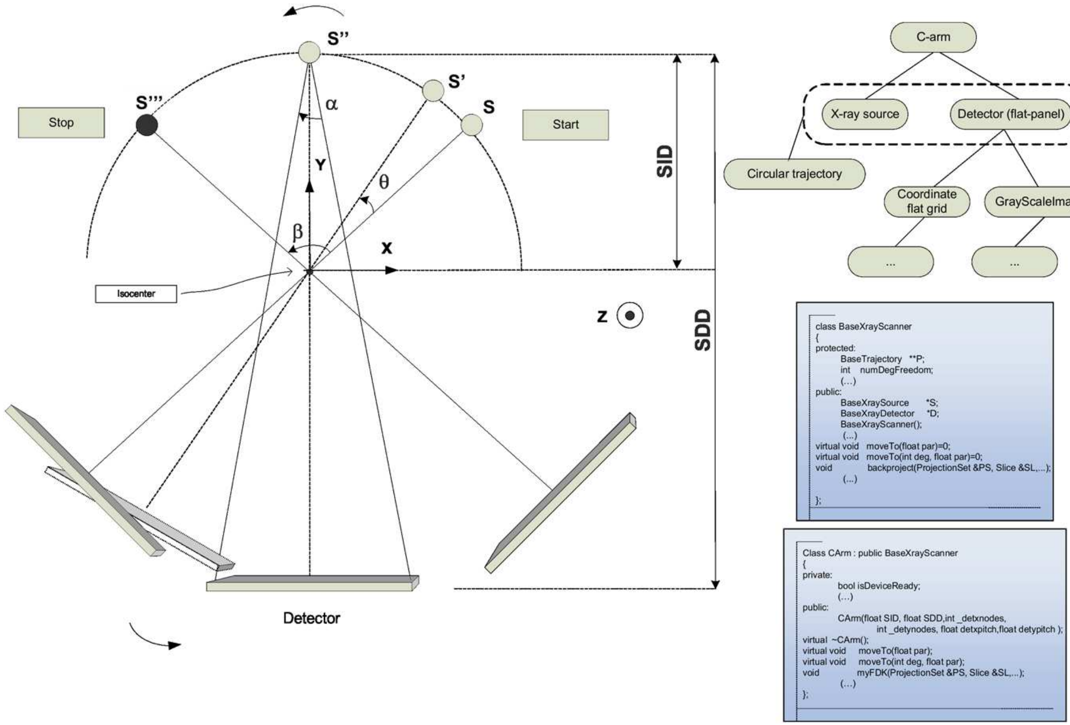

Figure 2. C-arm device configuration and relations to the RTCL components. On the left, the acquisition geometry in limited arc trajectory like a C-arm is shown. On the right, basic building blocks that constitute the construction of a CArm object scanner class. The CArm is derived from its parent, the BaseXrayScanner class

2.2 Integrating RTCL into PIRXI

The idea of integrating the library into a multi-purpose application for image reconstruction is a logical follow-up of the first medical and non-medical (e.g in the area of NDT) imaging applications based on it. The library is now a core component of a larger software application: the Platform for Image Reconstruction in X-ray Imaging – PIRXI. An initial version of the platform has been already created and is currently being used in the implementation of various image reconstruction tasks in the research activities of the team.

The GUI of PIRXI is developed in C/C++ and Qt. This allows a good portability of the code along different computing platforms and OSs. It has been tested on Windows and Ubuntu Linux.

It is a common situation when a researcher obtains CT projection data from external sources and spends significant amount of time trying to convert them into an appropriate format of the application he/she uses. PIRXI tries to deal with this problem and can provide a solution to reconstruction tasks using a wide range of scanning geometries and projection image formats. Based on the system of the .INI files and with the help of a rich set of keys, a large number of projection file naming, contents and data formats are transparently handled by the platform and the projections can be loaded and further used.

A snapshot of the GUI of the PIRXI platform running under Windows is shown in Figure 3. The GUI currently allows the definition of a whole reconstruction job. The user can interactively describe such a reconstruction task by providing information to the system (e.g. through a Dialogue), where he/she describes the general settings of the task. Common parameters include the description of the projection set (by means of data format, geometric acquisition settings, description of the detector's pixel size and metrics, location of data and destination of the processed files, etc.). The projection processing/preprocessing (e.g. filtering) follows, where again the task is easily performed through buttons on the GUI. Finally, the user can easily perform experiments and gain an understanding of the loaded/processed available data by choosing to reconstruct either central positioned slices or tomograms

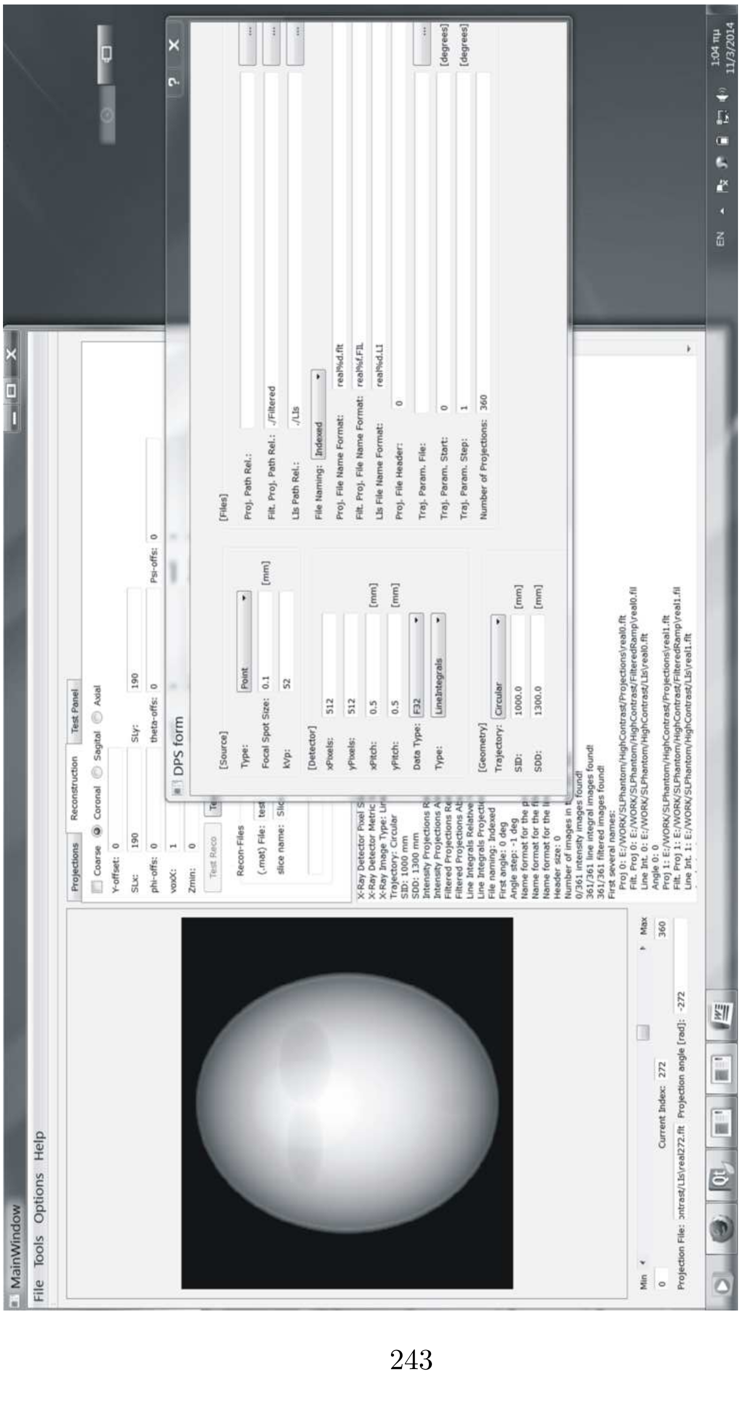

Figure 3. A snapshot of the GUI of PIRXI platform

of arbitrary orientation. Moreover, the possibility for a direct volumetric reconstruction is given. The image reconstruction method can be chosen from the already implemented ones through the GUI, where further options are provided in case the reconstruction algorithm demands additional input from the user (e.g. the arc in DTS or the projection angle spacing used for reconstruction).

2.3 Examples of using PIRXI in medical applications

Selected reconstructed tomograms using simulated data acquired in specific scanning trajectories are used as a demonstration of the tool. The use of simulated data is particularly useful in studying and analyzing reconstruction algorithms in principle, since data are free from distortions and mechanical inaccuracies inherent to radiographic units. Noise-free monoenergetic projection images of three simulated phantoms were acquired using an in-house developed tool, the XRAYImagingSimulator [2].

The first phantom is a modified (high contrast) version of the well known analytical Shepp-Logan phantom that approximates the human head and consists of 12 ellipsoids. The phantom was included in a cubic volume of size 190x190x190 and voxel size 1.

The second phantom is a 3D voxelized model of a metallic cylindrical implant (e.g. intramedullary tibial nail) used in interventional procedures in orthopedic surgery for the treatment of bone fractures. The implant consists of 8 screw holes at various locations and orientations, and is placed in three other cylinders that model a human leg (e.g. red bone marrow, bone and muscle). A detailed study on accurate localization of hole canals using CBCT, is presented in [9].

As a third example, a simulated 8cm complex uncompressed breast phantom [3] approximating the medium-sized breast was used. The model contains four clusters of microcalcifications (μCs) delivered in two different groups. In two different layers of the phantom, two clusters of 5μCs in one layer and two clusters of 6μCs, modeled as spheres/ellipsoids of calcium carbonate and of size 0.2 mm and 0.4 mm, are placed. The simulation parameters for image acquisition as well as the reconstruction settings used for all the phantoms are presented in table [1].

Table 1. Acquisition and reconstruction settings used along with the three simulated phantoms

	Phantoms		
Parameter/ Settings	**Shepp-Logan**	**Metallic implant**	**Uncompressed Breast**
Source-isocenter distance (SID)	1000 mm	1000 mm	600 mm
Source-detector distance (SDD)	1300 mm	1300 mm	665 mm
Number of views/Projections	360	121	25
Detector size	512x512 (pixels)	480x480 (pixels)	500x500 (pixels)
Pixel pitch	0.5mm	0.5mm	0.2 mm
Magnification factor	1.3	1.3	1.108
Reconstruction matrix/slice size	190x190x190	370x370	500x500
Source/Detector trajectory	Full 360^o circular trajectory, angular step 1^o	Circular isocentric rotation, 121^o limited arc, angular step 1^o	Circular isocentric rotation, 48^o limited arc, angular step 2^o
Reconstruction algorithm	FDK	FBP	FBP & SAA

2.3.1 CBCT reconstruction using the FDK algorithm

For the case of Shepp-Logan phantom, 360 projections images, acquired every 1^o step, were used for volumetric reconstruction using the FDK algorithm [10]. The main advantage of cone beam algorithms is the reduction in data collection time. With a single source, ray integrals are measured through every point in the object, in the time it takes to measure a single slice in a conventional two-dimensional scanner. The projection data can be expressed as a function of the source angle and the horizontal and vertical positions on the detector plane. The FDK algorithm is an approximate formula and represents a generalization of the 2D fan-beam reconstruction formula to the 3D case. The volume reconstruction is based on initial filtering and subsequent length correction weighting of the projection data followed by backprojecting a single plane within the cone, for each elevation along the z-axis. The final three-dimensional reconstruction is obtained by summing the contribution to the object from all tilted fan beams [8], which involves a final weighting that accounts for this tilt during backprojection. The FDK algorithm can be implemented with moderate computational requirements and delivers a satisfactory reconstruction quality for small cone angles (e.g. up to 10^o). The individual steps of this algorithm are already implemented in the RTCL.

2.3.2 DTS reconstruction using Shift and Add & Filtered Backprojection algorithms

For the breast phantom and the metallic implant phantom, DTS image reconstruction techniques were applied. DTS is a limited angle method of image reconstruction, where projection images acquired at regular angular intervals, and during a single acquisition pass, are used for reconstruction of planar sections [11]. In many applications (e.g. mammography) the source trajectory traces a limited circular arc, while the detector usually remains stable. In the current investigation, the acquisition geometry is isocentric. The acquisition geometry of isocentric Digital Tomosynthesis setup resembles that of the C-arm shown in Figure 2, but the angular range of the source-detector pair is usually much smaller. Important parameters for this acquisition geometry are once again the SID and SDD, as well as the acquisition range (denoted with ϕ) and the angular step θ. With the parameter α in Figure 2, the fan-beam angle is indicated. In the present example, 25 images of an uncompressed simulated breast were acquired in the limited arc -24^o to 24^o, with 2^o step (Table 1). Tomograms were further reconstructed using a simple backprojection technique (Shift and Add algorithm – SAA), similar to that of [11] and a Filtered Backprojection (FBP) algorithm. Both of these algorithms are implemented in RTCL. In both cases, the purpose was to bring in focus the planes of interest (e.g. the μCs). The Simple Backprojection algorithm was utilized, as it requires a straightforward implementation and minimal computational power and processing time efforts. However, since this technique introduces additional reconstruction artifacts (e.g. out-of-plane structures with high contrast tend to appear as low-contrast replicas in reconstruction planes), the FBP algorithm was also applied in an attempt to recover the loss of contrast especially for the small structures (e.g. the μCs). For the case of metallic implant phantom, a larger acquisition arc of 121^o was used with step of 1^o. In this case, only a FBP approach was followed for the reconstruction.

3 Results

Figure 4 demonstrates the outcome of the FDK reconstruction of the first phantom. Using projection images of the modified Shepp-Logan phantom, central three orthogonal to each other reconstructed slices (axial, coronal, saggital) and a slice at a plane $Z = -24$ mm away from the central plane, are presented.

Accordingly, below each reconstructed slice, line plot profiles (corresponding positions are marked with a white solid line in each reconstruction), are presented as compared to the original (dashed line).

The visual inspection of the reconstructed images and especially the comparison of the selected line profiles (in the reconstructions as compared to the original phantom) validate the correct implementation of the reconstruction algorithm using the RTCL.

In Figure 5, DTS reconstructions of a simulated uncompressed breast are shown. In the upper row, a FBP algorithm implemented with the help of the RTCL library is used for reconstruction, while in the bottom row, results after applying a SAA approach in corresponding locations, are presented. In both reconstruction approaches the μCs were found to be in-focus in the planes at $Z = -21$mm below and $Z = 9$mm above the central plane, which is considered at the isocenter. In the right part of Figure 5 and from up to down, zoomed recon-

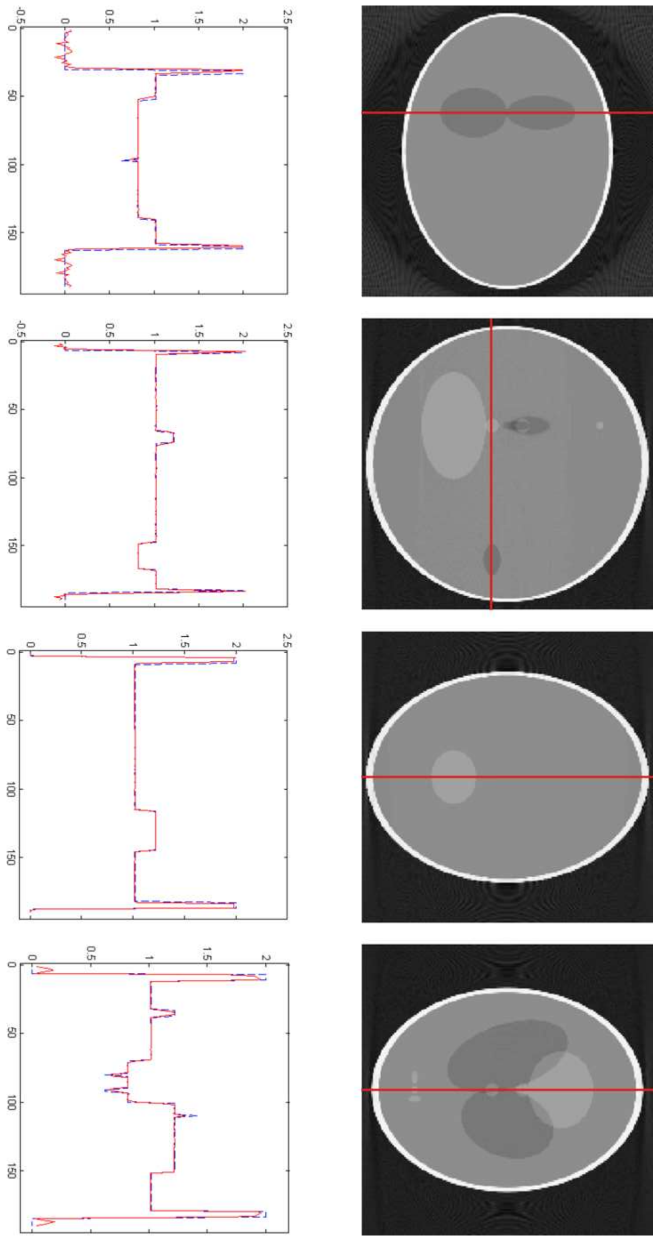

Figure 4. CBCT reconstruction of a modified Shepp-Logan phantom using the FDK algorithm implemented in the RTCL library. From left to right, line profiles (with solid lines) in the reconstructions at $x = 70$, $y = 95$, $x = 105$ and $x = 96$ (for the far right slice) at plane $z = -24$, as compared to the original (with dashed line)

structed regions of interest containing the features under investigation are presented, at $Z = -21$mm and $Z = 9$mm, after applying a FBP algorithm and after using SAA, respectively. Both groups of larger μCs (4mm diameter) are well visualized in the reconstructed planes. Regarding the smaller in diameter μCs (2mm), 2 out of the group of 5μCs from the plane at $Z = -21$mm and 1 out of the group of 6μCs were not observed at all in any of the reconstructed slices.

This is a common situation in Breast imaging tomography, since μCs with size smaller than 0.25mm are reported to have difficulties in detection. Moreover, tomographic reconstruction further away from the central plane of the isocenter introduces additional artifacts that overlay in some cases the features under investigation.

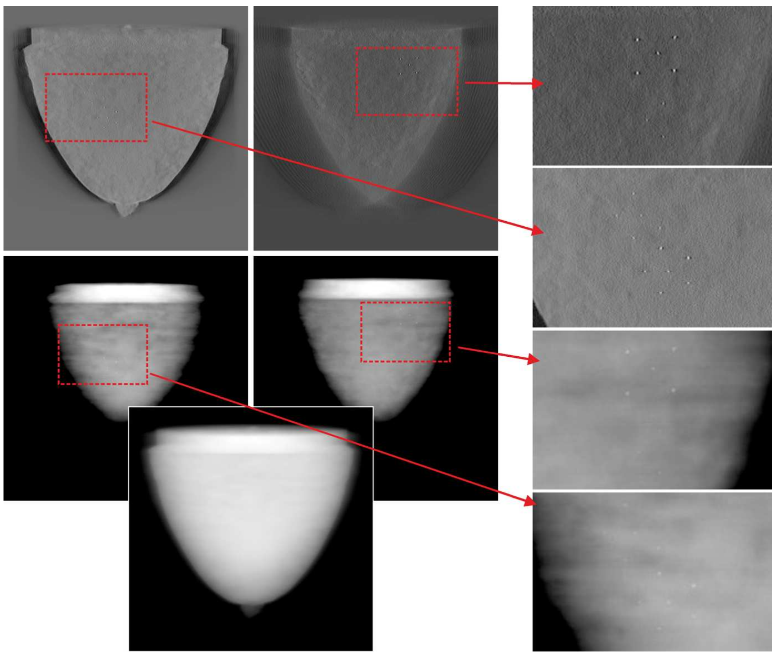

Figure 5. DTS reconstruction of a simulated breast using an implementation of a FBP reconstruction algorithm in RTCL (upper row) and a corresponding Shift and Add technique (bottom)

In Figure 6, DTS reconstructions of a simulated metallic implant are shown. Reconstructions were performed as previously with a FBP reconstruction algorithm using the RTCL library. 2D tomograms were reconstructed at “arbitrary” orientations by feeding the platform with Euler angles close to those that describe the phantom rotation around the principal axes, but not with their exact values.

The results present reconstructed slices almost “parallel” to the main axis of the implant, providing useful information for further image processing and analysis. The openings (e.g. hole canals) are in most cases well visualized.

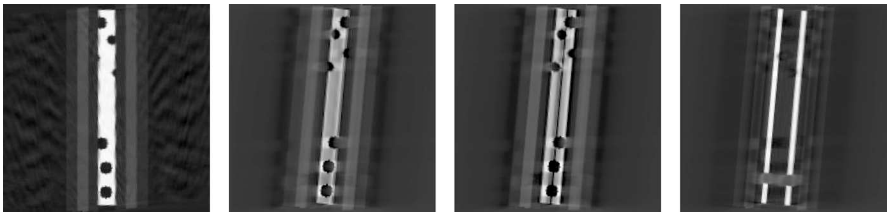

Figure 6. DTS reconstruction of a simulated metallic surgical implant

4 Conclusions

This paper describes the current structure of the RTCL library and the way it can be used for developing software applications within the field of the X-ray Computed Tomography (CT). The library is considered as the core component of an integrated software application – the Platform for Image Reconstruction in X-ray Imaging (PIRXI). Selected reconstructed slices from simulated data used in medical imaging, after applying CBCT or DTS reconstruction algorithms, were used for demonstration purposes. The current tests of both RTCL and PIRXI prove the flexibility of the new approach to image reconstruction research and algorithms implementation. The tools aim to facilitate any experimentation, study and development/implementation of reconstruction algorithms and scanning geometries and configurations in the Computed Tomography field.

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