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A realistic projection simulator for laboratory based X-ray micro-CT

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ABSTRACT

In X-ray computed tomography (CT) each voxel of the reconstructed image contains a calculated grey value which represents the linear attenuation coefficient for the materials in that voxel. Conventional laboratory based CT scanners use polychromatic X-ray sources and integrating detectors with an energy dependent efficiency. Consequently the reconstructed attenuation coefficients will depend on the spectrum of the source and the spectral sensitivity of the detector. Beam hardening will alter the spectrum significantly as the beam propagates through the sample. Therefore, sample composition and shape will affect the reconstructed attenuation coefficients as well.

A polychromatic projection simulator has been developed at the "Centre for X-ray Tomography" of the Ghent University (UGCT) which takes into account the aforementioned variables, allowing for complete and realistic simulations of CT scans for a wide range of geometrical setups. Monte Carlo simulations of the X-ray tubes and detectors were performed to model their spectral behaviour. In this paper, the implementation and features of the program are discussed. Simulated and real CT scans are compared to demonstrate the quantitative correctness of the simulations. Experiments performed at two different UGCT scanners yield a maximum deviation of 3.9% and 6.5% respectively, between the measured and simulated reconstructed attenuation coefficients.

1. Introduction

The "Centre for X-ray Tomography" of the Ghent University (UGCT; www.ugct.ugent.be) is a research facility specialised in high resolution X-ray computed tomography (CT). Currently 4 complementary state-of-the-art micro-CT scanners have been built at UGCT, two of which reach a spatial resolution well below 1 μm [1–3].

At UGCT a large variety of samples, both in terms of size and composition, is scanned for a wide range of applications. To optimise image contrast, ideal scanning conditions have to be created which will be different for each sample. Therefore, realistic simulations which take into account the influence of various scanning variables, such as emitted spectrum by the source, detector response characteristics, beam filtration and the sample itself, can be very useful to define the optimal scanner settings [4].

Several research groups have developed a simulation tool for X-ray imaging for different purposes, e.g. VXI [5–9], XRayImagingSimulator [10–12], ScorpiusXLab [13], XRSIM [14], etc. However, most of these tools are developed in-house to meet specific needs for their own research and are not readily available. Furthermore, thorough experimental quantitative comparisons with real CT scans are often not presented in literature. The intent at UGCT is to have a flexible, fast and accurate simulation tool which can be used in a routine way to test and define optimal scanner settings and which has been tested for its quantitative correctness by comparing real and simulated CT scans. Therefore, a GPU based program – Arion – has been developed to simulate radiographic projections, incorporating the physical aspects and limitations of laboratory based X-ray micro-CT.

The result of a CT scan is a virtual 3D representation of the sample composed of voxels. Each voxel contains a calculated grey value which represents the linear attenuation coefficient for the materials in that voxel. This linear attenuation coefficient is the product of the local density and mass attenuation coefficient, the latter being dependent on both the chemical element(s) present and the incident photon energy. Conventional laboratory based CT scanners use X-ray sources producing a polychromatic spectrum, in combination with integrating detectors with an energy dependent efficiency. The transmitted monochromatic intensity through the sample $I(E)$ is given by the Lambert–Beer law:

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$$I(E) = I_0(E)\exp(-\mu(E)d), \quad (1)$$

with $I_0(E)$ the intensity of the photon beam emitted by the X-ray source, $\mu(E)$ the linear attenuation coefficient, d the sample thickness and E the monochromatic photon energy. This law is used in reconstruction algorithms.

Consequently, the actually measured grey values in the voxels will depend on the incident X-ray spectrum and the spectral sensitivity of the detector. The polychromaticity will also induce effects such as metal artefacts and beam hardening, characterised by an upward shift of the average energy of the beam while it propagates through the sample. Therefore, also sample size, shape, elemental composition and density will have a significant influence on the resulting grey values. All these variables are taken into account in the simulation tool.

To model the polychromatic behaviour of source and detector, Monte Carlo simulations were performed for each X-ray tube and detector available at UGCT. The radiographic projections are computed using a ray-tracing technique which determines the total attenuation in a ray. The X-ray spectrum is divided into energy bins and for each detector pixel the contribution from each energy bin can be added, yielding a polychromatic projection image.

Arion is a stand-alone application, written in C++. The program is very flexible, allowing for instance to choose a wide range of geometrical setups. For every component – source, sample and detector – a position and orientation for every projection can be defined. Conventional CT setups such as circular and helical CT scans are readily available. A conveyer belt has been implemented as well, but also other (industrial) setups can be defined by the user and used for the simulations.

In this paper, Arion and its physical background is presented and thoroughly tested for its quantitative correctness. First, the general structure of the program and the Monte Carlo simulation of the sources and detectors will be discussed in Section 2. In Section 3, the physical background of the program will be explained. Finally, in Section 4 simulated and experimental CT data will be compared.

2. Material and methods

Fig. 1 shows a flowchart of the different steps during the setup of a CT scan simulation with Arion, illustrating the general structure of the program. These steps are implemented in a single graphical user interface (GUI).

The program includes several other tools in addition to the projection simulator itself, such as a material creator, phantom creator and Setup Optimiser. The material creator tool allows the user to generate the attenuation data for molecules, mixtures, such as concrete, soft tissue, etc. and solutions based on the mass fractions of the constituent elements. This data can then be used in the simulator. With the phantom creator a slice or stack of slices can be loaded to produce a phantom sample file which can be accessed during the scan setup. The Setup Optimiser uses functions of the projection simulator to evaluate the influence of different scanner settings in a straightforward way. After selecting a specific X-ray tube, tube voltage, beam filtration and detector type, the detected transmission of the polychromatic X-ray beam through a material or combination of materials can be calculated. Furthermore, several parameters of the emitted and detected spectrum are computed, as well as a measure for the expected amount of beam hardening.

For accurate simulations of a CT scan, the polychromatic behaviour for every component – source, sample and detector – has to be known. How this data is obtained will be discussed in this section.

2.1. Simulation of source and detector

For each type of X-ray tube and detector the polychromatic behaviour will differ according to their composition and design. For example, the entrance window and scintillator thickness will have a significant influence on the spectral sensitivity of a detector. So the polychromatic aspect of each available X-ray source and detector at UGCT has to be characterised separately. To achieve this, Monte Carlo simulations were performed using BEAMnrc (www.nrc-cnrc.gc.ca/eng/solutions/advisory/beam_index.html), taking into account the geometrical design of each specific component (Fig. 2). As a result, detailed but non-negligible effects such as for example the production of secondary radiation [15] in a transmission-type X-ray tube (see below), are included in the obtained data. Photon cross sections were imported from the XCOM Photon Cross Sections Database from NIST (www.nist.gov).

2.1.1. Source

Inside an X-ray tube, electrons are emitted from a hot filament and accelerated towards a target, usually tungsten. The electrons

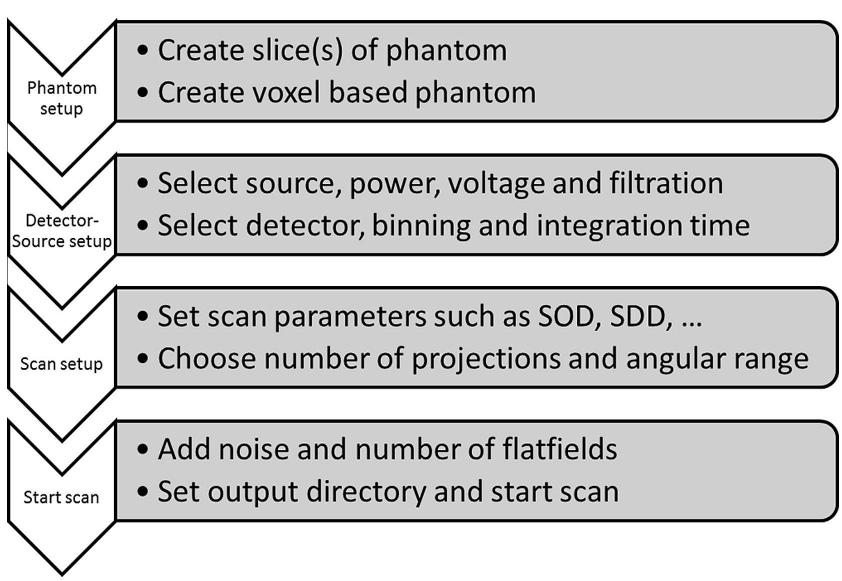

Fig. 1. Flowchart of the different processes during a CT scan simulation.