Contribution ID: **72** Type: **poster**

Validation of a μCT system simulation with a small-pixel photon-counting spectral detector

Photon-counting spectral detectors (PCD) have significantly advanced CT imaging by reducing image noise, enhancing contrast and spatial resolution, and enabling spectral imaging [1]. These benefits have extended to μCT imaging, where small-pixel (<100 μm) PCDs have allowed material-specific quantitative imaging at high spatial resolution [2]. Similarly, phase-contrast x-ray imaging (XPCI) has proven to be an important technique in laboratory μCT setups for the visualization of low-contrast structures [3]. These experimental advances create a demand for a new simulation tool that incorporates and accurately models the photon-counting detector spectral response and phase effects.

We present PEPIsim (https://baltig.infn.it/coathup/PEPIsim), a new and freely available simulation software written in Matlab. PEPIsim simulates the μCT imaging system available at the INFN's PEPI Lab [4], producing quantitatively accurate μCT images through the use of a validated detector model [5]. Propagation-based phase-contrast x-ray imaging (PBI) effects have also been included, expanding its utility to low Z materials such as soft tissues. This allows for a complete optimization of the phase-contrast, spectral x-ray μCT acquisitions performed at the PEPI Lab.

PEPIsim simulates the complete μCT imaging pipeline, from x-ray spectrum generation and detector response to projection image creation and the final CT reconstruction. A GUI allows users to configure a variety of experimentally relevant parameters involved in the simulation process including the imaging setup geometry, the x-ray tube settings, the detector characteristics, the object definition, and the reconstruction parameters, enabling highly customizable simulations.

PEPIsim has been experimentally validated using the photon-counting spectral μCT setup at the PEPI Lab, featuring a microfocus x-ray tube with a tungsten anode (source size: 5–30 μm) and a Pixirad-PixieIII detector [6] (650 μm thick CdTe sensor, 62 μm pixel size, 512×402 matrix, two thresholds per pixel, charge-sharing correction). Validation experiments were performed using a PMMA phantom (8 mm diameter) containing four material inserts (PE, PTFE, PVC, PEEK) each with a 2 mm diameter. Simulated and experimentally acquired images were compared across three key acquisition parameters: tube voltage (45 –100 kVp), source-to-detector distance (40 –133 cm), and magnification (1.35 –3.74 x).

Quantitative evaluation included attenuation coefficient accuracy, signal-to-noise ratio (SNR) in attenuation images, SNR in phase images, and the PBI-induced edge enhancement fringe visibility. Results demonstrated excellent agreement between simulated and experimental data, with attenuation values showing an average relative error below 2% and phase-contrast fringe visibility reproducing experimental measurements within 6% accuracy across the five tube voltage settings that were tested. The attenuation SNR and phase SNR had relative errors of 6.4% and 3.7% respectively across the five tube voltage settings. An example of a CT reconstruction of the PMMA phantom along with the PEPIsim simulated CT reconstruction of the same phantom are included in Figure 1. The phase-retrieved images of each of the attenuation images are also included.

The imaging system spectral response, including the combination of PCD response and the filtered x-ray tube spectrum was also validated by means of a detector threshold scan. The photon counts in both an experimental flatfield image and a simulated flatfield image were counted over a range of detector threshold settings, ranging from 10 keV up to the x-ray tube kVp in steps of 2 keV. This was repeated for seven different tube voltage settings ranging from 40 kVp to 100 kVp in steps of 10 kVp. Figure 2 shows the results of the detector threshold scan. There is good correspondence between the simulated and experimental images at all tested tube voltage settings. There was an average normalized root mean square error of 0.6% between simulated and experimental threshold scans averaged across all tested detector thresholds.

A key application of PEPIsim the optimization of acquisition parameters for diverse μCT samples. Its flexibility supports the development of tailored imaging protocols based on sample material and geometry, paving the way for improved experimental design and image quality. Furthermore, while PEPIsim has been developed to simulate the current imaging setup at the PEPI Lab, its modularity allows for different detectors to be incorporated as well, provided that their spectral response is known.

References

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Workshop topics

Applications

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