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Hybrid framework for feasible modeling of an edge illumination X-ray phase-contrast imaging system at a human scale

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ABSTRACT

Here, we present a hybrid approach for simulating an edge illumination X-ray phase-contrast imaging (EIXPCi) set-up using graphics processor units (GPU) with a high degree of accuracy. In this study, the applicability of pixel, mesh and non-uniform rational B-splines (NURBS) objects to carry out realistic maps of X-ray phase-contrast distribution at a human scale is accounted for by using numerical anthropomorphic phantoms and a very fast and robust simulation framework which integrates total interaction probabilities along selected X-ray paths. We exploit the mathematical and algorithmic properties of NURBS and describe how to represent human scale phantoms in an edge illumination X-ray phase-contrast model. The presented implementation allows the modeling of a variety of physical interactions of x-rays with different mathematically described objects and the recording of quantities, e.g. path integrals, interaction sites and deposited energies. Furthermore, our efficient, scalable and optimized hybrid Monte Carlo and ray-tracing projector can be used in iterative reconstruction algorithms on multi GPU heterogeneous systems. The preliminary results of our innovative approach show the fine performance of an edge illumination X-ray phase-contrast medical imaging system on various human-like soft tissues with noticeably reduced computation time. Our approach to the EIXPCi modeling confirms that building a true imaging system at a human scale should be possible and the simulations presented here aim at its future development.

1. Introduction

X-ray imaging serves as a visualization tool for structural variation of objects in biology and medicine. Image contrast in absorption imaging is produced by changes of the X-ray absorption coefficient arising from the attenuation of x-rays due to photoelectric absorption, Compton scattering, density differences and from variations in the thickness of the objects [1]. Moreover, attenuation contrast is sensitive to changes in the atomic number of elements in the specimen. Thus, structures within soft tissues are difficult to detect due to the small differences in the X-ray absorption coefficients. X-ray phase-contrast imaging (XPCI), which utilizes phase alteration and is based on probing refractive properties of the specimen by an X-ray beam traversing an object, can serve as an alternative source of contrast for revealing the internal structure of the sample [2]. The behavior of x-rays as they travel through a specimen can be described in terms of the complex refractive index [2]. Hence, changes due to refraction can be visualized as a phase-contrast signal from soft tissues to characterize, for example, tumors in regions of the human thorax or brain [3]. Different XPCI methods have been developed for detecting the angular deviation in refraction of x-rays and to capture phase variations using synchrotron sources [4,5] or in the laboratory environment [6–8]. However, extensive efforts are being made toward clinical implementation of XPCI techniques, increases in the imaging volume and dose reduction to imaging specimens [9].

Previous investigations have reported the feasibility of implementing an X-ray tracing approach in a Monte Carlo (MC) simulation [10]. More recently, preliminary examinations on the possibility of including coherent propagation and diffraction based on wave-optics have been presented [11]. The fusion of wave-optics and X-ray tracing with the reconstruction of the phase from the path length [12] has also been proposed to reproduce XPC images. Thus, we exploit further such methods, developing a robust and feasible computation framework with a high degree of accuracy, tailored to edge-illumination XPC imaging.

A very powerful and efficient approach to modeling, evaluating, optimizing and predicting the realistic performance of an optical imaging system can be based on the use of ray-tracing methods. Computationally intensive problems such as X-ray phase-contrast image processing and multi-dimensional reconstructions

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can be acquired using complex algorithms dedicated to graphics processing units (GPU) that lead to relatively higher image quality and diagnostic efficiency [13]. The quality of the reconstructed image improves with the accuracy of the physical model assumed in the numerical projector; however, at the price of increased computing time. Numerous implementations of iterative reconstruction algorithms use projectors based on rotation and convolution. Such an approach usually involves approximations of the physical process of the propagation of x-rays. More accurate modeling can be obtained using ray-tracing, or Monte Carlo simulations of the system.

Several mathematical approaches are available for describing optical objects of interest in ray-tracing applications. But, the use of implicitly defined volumes often limits the usefulness of the ray-tracing computations to ideal cases. The simulation of errors shall extent beyond such models and must consider algorithms based on data from real surfaces (i.e. meshes) and/or statistical parameters. Nonetheless, the implementation of an X-ray tracer which can scale computations for multiple GPU systems and work with different types of objects and images (voxel based, 3D triangle mesh, polynomial representation) is a complicated and time-consuming task. Moreover, a code optimized for a particular type of graphic cards may not be easily transferable to other hardware, which can be a nuisance as GPU technology is advancing rapidly. These difficulties can be to a large extent alleviated by using the OptiX ray-tracing engine developed by Nvidia, which provides a flexible and versatile platform for developing algorithms involving ray tracing and using the computing potential of the GPUs [14].

In this paper, we describe the application of the OptiX ray-tracing engine for accurate and robust modeling of X-ray propagation in the EIXPCi system. It can be used as a fast MC simulator as well as an X-ray tracing projector in volumetric iterative reconstruction algorithms. Furthermore, we propose a sequentially defined X-ray tracing scheme for X-ray phase-contrast medical imaging systems using non-uniform rational B-splines (NURBS) surfaces [15] to model ray interaction with human scale organs (e.g. in the human head and thorax) more accurately.

2. Materials and methods

2.1. Edge illumination x-ray phase-contrast imaging simulation with an OptiX ray-tracing engine

Among the existing XPCi methods, the edge illumination XPCi technique has the potential for widespread application, as it is based on a straightforward operating principle (see Fig. 1) [9], which also requires a fast and robust reconstruction framework. The EIXPCi method can be implemented to work with conventional X-ray tube sources and easily scaled up to large fields of view [16] to acquire projections of adult human anatomy.

A detailed description of the EIXPCi concept can be found elsewhere [16]. In general, we introduced all the elements of the EIXPCi system to our OptiX simulation. The post-sample detector mask is placed in contact with the detector, and it serves the purpose of creating insensitive regions along the separation between adjacent pixel rows (or columns) [16]. The pre-sample mask is placed immediately before the sample, and it creates an array of individual beamlets each one impinging on the edge of the detector pixels, as defined by the detector mask. It is worth noting that the pre-sample mask prevents unneeded radiation from traversing the object hence, ensuring low dose accumulation, which is a highly desired quality in medical X-ray imaging. In order to model the method with a diverging beam from a conventional X-ray tube source, it is then sufficient to scale down the dimensions of the sample mask in order to take the beam divergence into account. Due to the differential nature of projection images in EIXPCi, the refraction angle is proportional to the gradient of the phase shift $\phi(x,y)$ [16]

$$\Delta\theta_{x,y}(x,y) \approx \frac{\lambda}{2\pi}\left|\vec{\nabla}_{x,y}\phi(x,y)\right|, \qquad (1)$$

where λ is the wavelength, $k = \lambda/2\pi$, and z is the direction of propagation. The phase shift $\phi(x,y)$ is given by the integral of δ along the z direction $\phi(x,y) = -k \cdot \int \delta(x,y,z)dz$.

Particular elements of an imaging system are defined in their own system of coordinates. X-ray tracing is sequential: for every element the distances of the source and detector plane, respectively, are known with reference to the preceding element. At each intersection with an element the coordinate system assigned to the beam changes into that of the optical element, until it reaches the detector plane. To follow the reflections of the x-rays emitted by the source, we compute the intersection points of every single X-ray with all elements of the EIXPCi system as described in Section 2.7.

In our simulation the intersection points are directly determined by solving the equation system containing the analytical forms of the NURBS surfaces and the X-ray parametric equations. Since the NURBS are parametric functions, the X-ray–NURBS intersections are computed using the *Intersection module* and *Material module* described below. At every intersection point, the auxiliary normal vector to the surface is computed from the surface gradient; thus the intersection point becomes the new starting point for the X-ray after interaction with the element of the system or the object. The direction of the ray is changed following the boundary conditions at the surface (for apertures). The projection of the beam is recorded at the detector plane, allowing the calculation of the various parameters (intensity, spatial and angular distributions, etc).

The OptiX ray-tracing engine [17] is a programmable system designed for highly parallel architectures built on the key observation that all ray-tracing based algorithms may be represented as a set of similar components. The OptiX library is equipped with a low level engine focused on the fundamental computations required for the X-ray-tracing and this can be highly useful for EIXPCi modeling. The engine provides a mechanism for coding interactions of rays with a predefined set of geometrical objects without referring to concepts specific to computer graphics, e.g. lights, shadows, reflections etc. The whole physics of the ray-object interactions in the EIXPCi simulation is left to be implemented by the user.

Our OptiX-based simulation framework provides an abstract ray execution model as a sequence of user-defined modules. The execution model, combined with data stored in buffers (e.g. object geometry and properties, interaction coefficients, etc.) and additional data stored in per-ray data structures (e.g. photon energy, interaction types and sites), is suitable for the implementation of various types of ray-tracing based algorithms from the standard rendering algorithms to more sophisticated applications such as

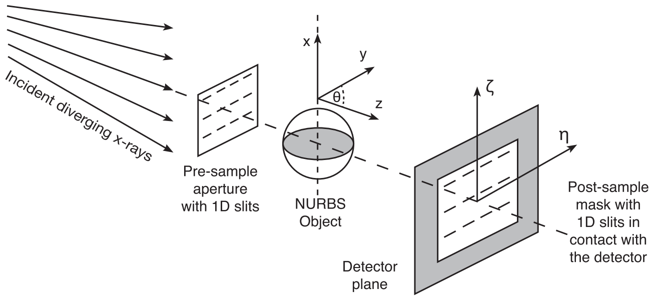

Fig. 1. Schematic illustration of the EIXPCi system concept.

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