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Rapid simulation of X-ray transmission imaging for baggage inspection via GPU-based ray-tracing

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ABSTRACT

We present a pipeline that rapidly simulates X-ray transmission imaging for arbitrary system architectures using GPU-based ray-tracing techniques. The purpose of the pipeline is to enable statistical analysis of threat detection in the context of airline baggage inspection. As a faster alternative to Monte Carlo methods, we adopt a deterministic approach for simulating photoelectric absorption-based imaging. The highly-optimized NVIDIA OptiX API is used to implement ray-tracing, greatly speeding code execution. In addition, we implement the first hierarchical representation structure to determine the interaction path length of rays traversing heterogeneous media described by layered polygons. The accuracy of the pipeline has been validated by comparing simulated data with experimental data collected using a heterogenous phantom and a laboratory X-ray imaging system. On a single computer, our approach allows us to generate over 400 2D transmission projections (125×125 pixels per frame) per hour for a bag packed with hundreds of everyday objects. By implementing our approach on cloud-based GPU computing platforms, we find that the same 2D projections of approximately 3.9 million bags can be obtained in a single day using 400 GPU instances, at a cost of only $0.001 per bag.

1. Introduction

X-ray imaging techniques are extensively used at airports and other controlled access facilities to detect contraband in luggage and other packages [1–3]. In the recent years, with evolving threat concerns in aviation security, the focus has shifted from the detection of metallic weapons to illicit explosives [4]. Unlike metallic threats, explosives are difficult to detect because they have X-ray properties similar to stream-of-commerce compounds and cannot be distinguished by shape alone. Thus, it is crucial to understand the fundamental performance of various scanner design choices in order to improve the system's threat detection performance.

By viewing the imaging system as an information channel and the X-ray detection as a task-specific problem, the ultimate performance limit can be measured by the amount of task-related-information passing through the system [5]. Such information-theoretic measures provide a rigorous metric [6] to evaluate the performance of X-ray material-based threat detectability without the confounding effects of processing algorithms. System parameters can be optimized by analyzing the information content of X-ray measurements obtained from stream-of-commerce and threat materials for different settings of system characteristics. However, in order to capture the statistical variations of baggage contents in high dimensional space, tens of thousands to millions of bags randomly packed with assorted stream-of-commerce items should be recorded and measured for each parameter optimization. This required data is sufficiently diverse and large that data acquisition via a real X-ray scanner is unattainable. Moreover, it is impractical and sometimes impossible to build a new machine for each parameter exploration. As an alternative, we need computer simulation tools to model X-ray scanning systems, convert plausible bag descriptors into 3D ensembles, and rapidly generate the large number of required measurements.

In contrast to the simulation needs of the medical and physics communities, we need to rapidly generate transmission projection images and to handle 3D bags with arbitrary internal composition and structure. To date, there are two main classes of X-ray simulation algorithms—probabilistic methods based on Monte Carlo trials and deterministic methods based on Beer's attenuation law. Monte Carlo approaches [7–9] simulate very accurate X-ray physics, but they are computationally expensive due to their stochastic nature (even with

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GPU-accelerated algorithms [10,11]). Alternatively, deterministic approaches with ray-tracing [12] have shown potential for computing X-ray transmission measurements within a short period of time.

Depending on the choice of descriptor approach, deterministic simulation of X-ray imaging can be implemented through either ray-voxel tracing [13,14] or ray-triangle tracing [15,16]. A voxel is a natural volumetric representation and a cheap primitive to intersect. However, a high resolution 3D voxel grid is needed to achieve good image quality, resulting in huge data sets compared to those represented by polygons. Although this memory constraint can be alleviated for simple scenes via discrete ray tracing [17] using an octree, it is unfit for representing baggage, which requires models of a wide variety of stream-of-commerce contents. We have chosen to use triangle meshes as the object descriptors because the bottleneck of ray-triangle tracing algorithms have been overcome via massive parallelism on GPUs [18–20]. Previous studies have shown that the GPU-based ray-tracing can be many times faster than even a multi-core, hyper-threaded CPU [21–23].Very recently, a simulation code [24,25] has been reported for X-ray imaging of triangle-meshed objects using a GPU-implementation based on the L-buffer techniques [15]. Intersections between rays and facets representing objects are quickly identified by mapping the 3D scene into a 2D texture. Nevertheless, this simulation method only tackles homogeneous polygonal objects, while real bags typically contain heterogeneous nested structures (e.g., explosives concealed in the battery compartment of a laptop computer).

In this paper, we present a new pipeline for rapid simulation of X-ray attenuation through complex polygon objects by making use of GPU-based ray-tracing techniques. This pipeline models all essential properties of commercial X-ray imaging systems with sufficient accuracy. A novel object description file along with a hierarchical data structure is introduced to describe volumetric and material information for a realistic bag model. To our knowledge, this is the first X-ray simulation that tackles object heterogeneity using a polygon object descriptor. The overall speed of the simulation pipeline is accelerated by making extensive use of the highly optimized NVIDIA OptiX ray tracing API to track photon-matter interactions. We conduct a qualitative validation of our approach by comparing simulated data with measurements obtained from a real X-ray imaging system. Although this pipeline was initially designed for studies of X-ray threat detection in the context of aviation baggage screening, it could be applied in the development, optimization, and evaluation of other non-destructive X-ray detection systems, such as medical diagnostic or quality assurance systems.

This paper is structured as follows. Section 2 contains a brief review of the ray-tracing algorithm for simulating X-ray measurements. The implementation of the components of a generic X-ray imaging system is described in Section 3. The simulation scheme is presented in Section 4. In Section 5, the simulated results for our heterogeneous, custom phantom are validated against experimental measurements and the performance of the presented pipeline is assessed in terms of both speed and accuracy. Finally, Section 6 provides conclusions as well as suggestions on future work.

2. Overview of X-ray imaging simulation strategy

We model photons as a set of rays emitted from point sources toward the detector pixels. The number of photons of energy E arriving at pixel k of the detector array is given by the attenuation law [12–16],

$$I_k(E) = \Phi(E,\theta,\phi)\Delta\Omega_k(\theta,\phi)\sum_i \exp[-\mu_i(E)l_i], \tag{1}$$

where $\Phi(E,\theta,\phi)$ denotes the source strength (the number of photons of energy E emitted per unit time per steradian). $\Delta\Omega_k(\theta,\phi)$ is the solid angle of the corresponding pixel as viewed from the center of the X-ray source and is given by

$$\Delta\Omega_k = \frac{\Delta S_k \cos\theta_k'}{r_k^2}, \tag{2}$$

where ΔS_k is the surface area of detector pixel, r_k is the distance from the center of the source to the pixel, and a θ_k' is the angle between the pixel surface normal and the ray from the source to the pixel center. The intensity of the primary X-ray beam is reduced as it penetrates through the material layers of the bag object. The number of transmitted photons at each energy is determined by a combination of the linear attenuation coefficient μ_i and the path length l_i of the ray through material i. For each ray, l_i is calculated by tracing the position of intersections between that ray and the corresponding object surface. The linear attenuation coefficient can be re-written as

$$\mu_i(E) = \rho_i(\sigma_{iA}(E) + \sigma_{iR}(E) + \sigma_{iC}(E)), \tag{3}$$

where ρ_i is the density and σ_{iA}, σ_{iR}, and σ_{iC} are the cross sections for *photoelectric absorption*, *Rayleigh scattering*, and *Compton scattering*, respectively. Pair production is neglected as the energies in our security screening application never exceed 200 keV.

This X-ray linear attenuation formula, combined with our ray-tracing approach, can calculate direct photon attenuation from the three interactions, but *does not* consider changes in incident photon energy or direction due to Compton or Rayleigh scattering effects. However, some of those scattered photons will strike the detectors and be recorded as a background signal. We address this scatter influence by including an overall DC offset to the measured photon signals. This DC offset is calculated as the product of the number of scattered photons along all rays with a scale parameter, whose value can be tuned to match the observed scatter background from a relevant experiment. A modification to the simulation to more fully account for the effects of scatter has been developed and will be described in a future paper.

3. Modeling of X-ray imaging chain

As shown in Fig. 1, a standard virtual radiographic imaging chain consists of three main components: the object, the X-ray source(s), and the detector(s). X-ray projections are made by measuring the number of X-ray photons transmitted through the objects and recorded at the detector. As the X-ray attenuation coefficients of materials in the objects are energy-dependent, additional material information can be acquired from spectral measurements. Therefore, the components of simulated system are modeled with geometric and spectroscopic characteristics. Geometric parameters such as size, shape, position, and

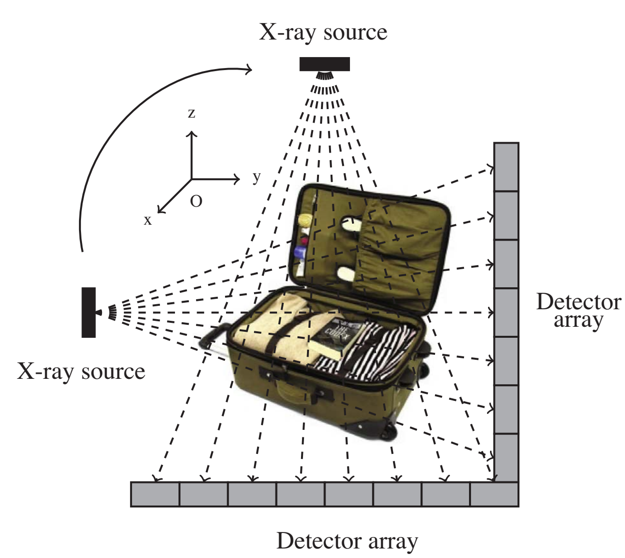

Fig. 1. Notional schematic of an X-ray imaging system consisting of a rotating source and a L shape detector array.