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X-ray simulations with gVirtualXray in medicine and life sciences

F. P. Vidal^{1,2}, S. Afshari³, A. Albiol⁴, F. Albiol⁵, A. Corbí Bellot⁶, A. L. Brun^{7,8}, C.-Y. Chou³, P. Desbarats⁸, M. García⁹, J.-F. Giovannelli¹⁰, C. Hatton¹¹, A. Henry¹¹, G. Kelly¹², C. Michelet⁷, R. P. Mihail¹³, M. Racy¹⁴, A. Rouwane⁷, H. Sez nec⁷, A. Sújar⁹, J. Tugwell-Allsup¹⁵, and P.-F. Villard¹⁶

¹ UKRI-STFC Scientific Computing, Daresbury Laboratory, UK

² School of Computer Science & Engineering, Bangor University, United Kingdom

³ Department of Biomechanics Engineering, National Taiwan University, Taiwan

⁴ PRHLT Research centre, Universitat Politècnica València, Spain

⁵ Instituto de Física Corpuscular, CSIC-Universitat Politècnica, Spain

⁶ Escuela Superior de Ingeniería y Tecnología - Universidad Internacional de La Rioja, Spain

⁷ Univ. Bordeaux, CNRS, LP2I Bordeaux, UMR 5797, F-33170 Gradignan, France

⁸ Univ. Bordeaux, CNRS, Bordeaux INP, LaBRI, UMR 5800, F-33400 Talence, France

⁹ Grupo de Modelado y Realidad Virtual, Universidad Rey Juan Carlos, Spain

¹⁰ Univ. Bordeaux, CNRS, Bordeaux INP, IMS, UMR 5218, F-33400 Talence, France

¹¹ Scalian DS, Rennes, France

¹² Shrewsbury and Telford Hospital NHS Trust, United Kingdom

¹³ Department of Computer Science and Engineering Technology, Valdosta State University, Georgia, USA

¹⁴ Salford Royal Infirmary, Manchester, United Kingdom

¹⁵ Betsi Cadwaladr University Health Board (BCUHB), Ysbyty Gwynedd, United Kingdom

¹⁶ Université de Lorraine, CNRS, Inria, LORIA, Nancy, France

Abstract

gVirtualXray (gVXR) is a programming interface framework to simulate realistic X-ray projections in realtime on graphics processing units (GPUs). It solves the Beer-Lambert law (attenuation law) using a deterministic X-ray simulation algorithm based on 3D computer graphics, namely rasterisation. Implemented as multi-pass rendering makes it more computationally optimal than the more intuitive ray-tracing technique. Although written in C++ using OpenGL and its shading language (GLSL) to leverage the GPU, gVXR is available for other programming languages such as Python. Extensive validation studies, including comparisons with Monte Carlo simulations and real experimental data, have confirmed the accuracy of gVXR's simulations. gVXR was initially used in medical virtual reality (VR) for training purposes. It was then used in medical physics, and high-throughput data applications including mathematical optimisation and machine learning (ML). Micro-imaging studies on the C. elegans biological model are also reported.

CCS Concepts

• **Computing methodologies** → **Real-time simulation; Physical simulation; Virtual reality; Machine learning; Applied computing** → **Physics**;

1. Introduction

gVirtualXray (gVXR) is an application programming interface (API) to simulate realistic X-ray projections in realtime on graphics processing units (GPUs) (<https://gvirtualxray.sourceforge.io/>). It is written in C++ using OpenGL and its shading language (GLSL). Wrappers are provided for some of today's popular programming languages, including Python, C# and Java.

Solving the Beer-Lambert law (attenuation law) with deterministic X-ray simulation algorithms is often described using ray-tracing due to the intuitiveness of this approach. It could be implemented with GPU programming techniques such as CUDA. However, that

would be computationally suboptimal. Freud *et al.* demonstrated on the central processing unit (CPU) that a rasteriser is much more computationally effective and leads to the same level of accuracy [FDLB06]. In this case, the X-ray attenuation through matter is calculated as a rendering problem, which can be solved using blending (transparency) and a shading language [VGF*09]. Using multi-pass rendering, it is even possible to add further levels of realism, including polychromatism (spectra made of X-ray photons of multiple energies) and focal spot (the finite size of the X-ray source) [VGF*10, VV16]. Scintillation is now modelled to further increase realism [PWTA*23].

Simulations performed with gVXR has been benchmarked against i) images generated with a state-of-the-art Monte Carlo

simulation tool, Geant4, developed by CERN, and ii) experimental data (digitally reconstructed radiographs (DRRs), computed tomography (CT) slices, and a digital radiograph (DX)) acquired with clinically utilised devices [VV16, PWTA*23]. In every case, simulations performed with gVXR were proven to be very accurate.

gVXR has been used in a wide range of applications, including medicine and biology. Some have been presented at conferences organised on behalf of Eurographics [VGF*09, VGF*10, VV15, SMV*17, SKGV19, WMAM*19]. This entry to the Dirk Bartz Prize provides a comprehensive review of such applications.

2. Applications

Historically, gVXR was used in medical virtual reality (VR) for training purposes (e.g. haptic femoral nailing simulator [RBTB21], interactive teaching tool for medical radiography [SKGV22] and catheterization and angiography positioning simulation [ZQLH18]). It was then used in medical physics to study motion artefacts in chest CBCT [VV15] and propose a new densitometric radiographic imaging [ACA19]. It is also used in high-throughput data applications including mathematical optimisation (e.g. registration of 3D surfaces onto patient-specific radiographs) [WMV21] and machine learning (ML), including segmentation, material decomposition [AC24], nodule detection, real-time denoising [AFE*21], and generative artificial intelligence (AI) [HLL*20]. We report here some of these applications.

2.1. Education

Realistic simulations provide a more immersive and engaging learning experience, helping students better understand and retain complex concepts associated with imaging techniques and acquisition. The closer the simulation experience is to mimicking real-life scenarios, the better it refines students' technical skills and prepares them for clinical placement. Simulation provides a controlled and safe environment where students can repeat practice (multiple image acquisition) and make mistakes and experiment with acquisition parameters without risking patient safety from the use of ionising radiation. This build student's confidence before transitioning into real clinical environments. It is also a great way to expose students to understanding clinical scientific computing skills that may inspire them to develop their own simulation in the future. With AI and significant technology advancements within Radiology, it is important to use different approaches to training and education to ensure sufficient pipeline of staff but also expose students to different types of technology early in their career to nurture that digital capability and innovation.

2.1.1. Haptic femoral nailing simulator

gVXR was a core component in the development of a VR haptic orthopaedic surgical simulator, where it provided real-time fluoroscopy images via a user-controlled virtual c-arm [RBTB21]. Orthopaedic surgery (and particularly intramedullary nailing) requires the ability to operate through minimal incisions using tactile feedback and static 2D fluoroscopy image guidance, and so effective and realistic image intensifier functionality is an essential component of such a device. The gVXR software was converted for use within the 3D environment by Toia Ltd (<https://toia.tech/>).



Figure 1: The simulator environment as seen through the VR headset, with the image intensifier images displayed on a virtual screen.

The virtual X-ray source was placed in the corresponding location on the virtual c-arm and the tissues, bone, tools and metalwork were assigned attenuation values to provide appropriate images. The live video feed produced by the software was converted to static images by the means of a camera relay system – the output video was displayed on a virtual screen outside the view of the user, with a camera taking snapshots and displaying them on the virtual image intensifier screens as required (Fig 1). This provided the user (interacting via a VR head-mounted display and haptic drill handle) with an unparalleled level of realism and training value, as evidenced by the feedback from the orthopaedic surgeons during simulator validation.

2.1.2. Interactive teaching tool for medical radiography

Trainees in projective radiography must balance producing optimal images with minimizing radiation exposure. Students are still learning with a book full of static images and, although they participate in real clinical environments, their practice is constrained by the risks of radiation exposure to living tissues. In this simulator (see Figure 2, gVXR and 3D animation techniques allow feasible anatomical models to be imported, repositioned, modified to get x-Ray images instantly [SKGV19, SKGV22]. Interactive patient positioning, virtual environment where users can adjust X-ray device parameters, and instantly visualizations of the resulting radiograph makes this software useful and suitable for teaching Projectional Radiography, according to a face and content validation.

2.2. Medical physics

2.2.1. Motion artefacts in chest CBCT

gVXR was employed to simulate motion-induced artefacts in CT image reconstruction, with a specific focus on respiratory motion [VV15]. A respiratory motion model was developed, building upon prior research designed for training purposes [VVH*09]. The active movements of the primary respiratory muscles were modelled, incorporating a combination of rigid-body kinematic motion

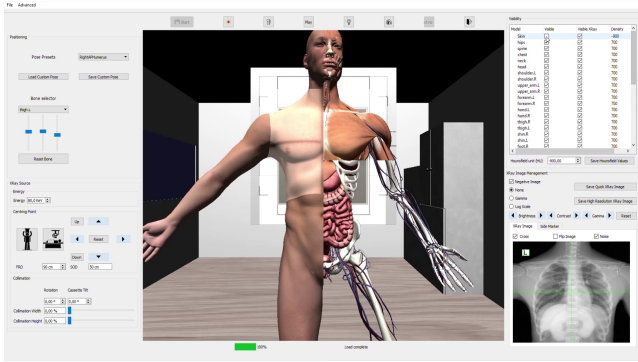


Figure 2: Interface of the Projectional Radiography Simulator.

for the ribs and active deformation modelling for the diaphragm. Other organs influenced by respiration deform passively, driven by the movements of these primary muscles. To achieve this, hybrid computing was utilised, with motion computations performed on the CPU and CT rendering executed on the GPU. The simulation was validated using multiple clinical images from patient datasets. Simulation parameters were optimised using a genetic algorithm, enabling precise reproduction of physiological motion dynamics. CT volumes reconstructed from X-ray projections simulated without respiration did not have motion artefacts, whereas they did when respiration motion was taken into account in the simulation.

2.2.2. New densitometric radiographic imaging modality

Typical X-ray radiographs are acquired using a single image at a given tube voltage (see Figure 3a). These images provide quantitative information about tissues densities. However, due to the physical limitations, it may not be possible to appropriately image both soft and bony regions. To improve contrast, dual-energy X-ray absorptiometry (DXA) can be used. DXA combines two radiographs produced at different voltages (i.e. one low and one high), which increases the radiation dose delivered to the patient.

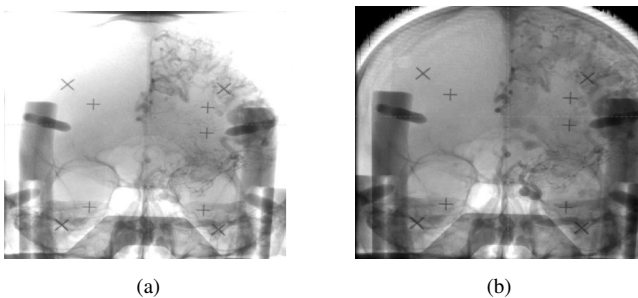


Figure 3: Examples of (a) X-ray radiographs and (b) corresponding densitometric images.

Using a contour sensor (depth camera), e.g. the well-known Microsoft Kinect, it is possible to measure the patient's volume and substitute one of the radiographs with one simulated with gVXR [ACA19]. In this case, it is important to calibrate the system so that the virtual patient, the real patient, and the X-ray device

are registered to fuse the real and simulated radiographs. The final images shown in Figure 3b exhibit an improvement in brightness and contrast: Areas that were overexposed are no longer.

2.3. Registration of a generic 3D hand model onto 2D radiographs using optimisation

Rheumatoid Arthritis (RA) is a chronic autoimmune disease causing destruction of the synovial joints of the hands to systemic inflammation, with hand stiffness and pain being the most common at the time of diagnosis. The most common imaging modality used to confirm joint damage is standard X-ray radiographs. Posterior anterior (PA) view of the hand involves the patient placing their hand flat on the sensing surface, allowing the radiologist to assess soft-tissue swelling and joint damage. Wen *et al.* [WMAM*19, WMV21] used gVXR to register a generic synthetic model of a hand to a real radiograph in PA view. This was formulated as an optimisation problem and solved using covariance matrix adaptation evolution strategy (CMA-ES) to recover the pose of the hand. The problem is non-trivial since the human hand is highly articulated with 27 degrees of freedom (DOF). Individual bones were scaled to account for anatomical variability. The results obtained were good, with low projection errors as seen in the Figure 4.



Figure 4: Example of registration results.

2.4. Machine learning

2.4.1. Lung nodule detection in 2D radiographs

Deep learning models are a promising approach to enhance medical image analysis. However, their performance is limited by the size, quality, and diversity of available training datasets. Incorporating synthetic data into training datasets can address the lack of medical imaging data. The combined use of a virtual anthropomorphic model with gVirtualXRay enables the rapid generation of large synthetic datasets. By injecting artificial lesions, deforming organ shapes and adjusting scanner settings, it is possible to replicate the variability found in real datasets. In the case of pulmonary nodule detection, training a YOLOv8 detection model on a mixed dataset composed of real and synthetic radiographs generated by gVXR, improved nodule detection performance by 32%, compared to training exclusively on real data. These preliminary results underscore the potential of gVXR to generate automatically labelled synthetic data of sufficient quality for training diagnostic models, thereby addressing the challenge of data scarcity in medical imaging research.

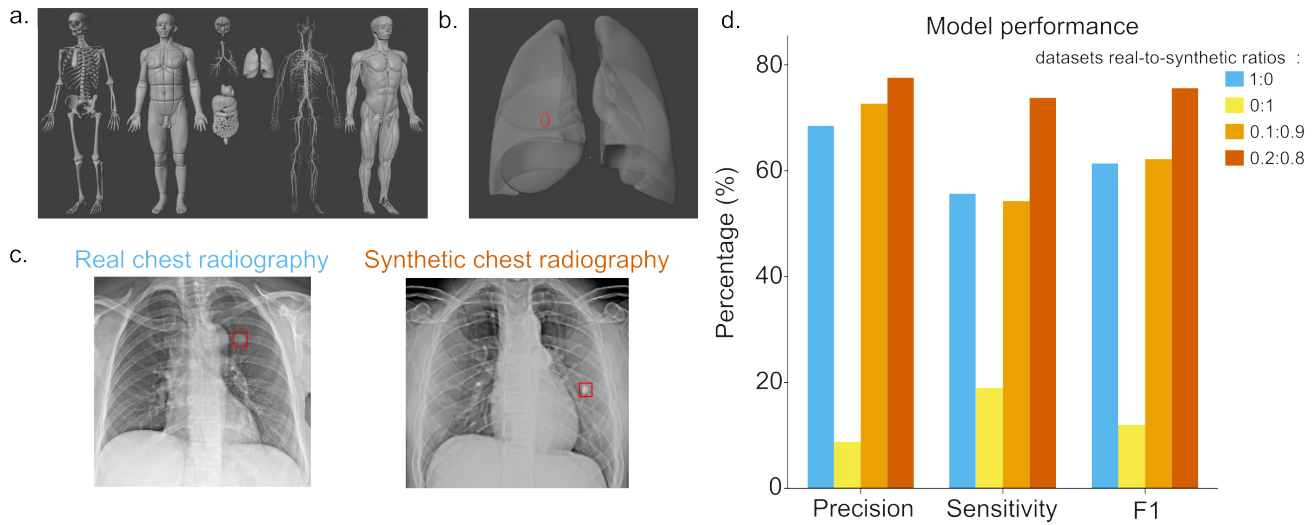


Figure 5: a. Virtual anthropomorphic model (from Z-anatomy). From left to right : meshes represent bones, skin, visceral organs and brain, blood vessels, muscles b. Example of a synthetic lung model with an artificially inserted nodule (red) c. Example of a real chest radiography (left) from NODE21 dataset, and synthetic chest radiography (right). Nodules bounding box in red d. Model performance as a function of each training dataset.

2.4.2. Spectral CT data simulation and material decomposition

The ability of gVirtualXRay to simulate spectral CT data plays a crucial role in advancing material decomposition techniques within medical imaging. By generating synthetic datasets across high-energy, low-energy, and conventional CT spectra, gVXR provides essential training data for deep learning models in material decomposition [AC24]. These models leverage pairs of reconstructed CT images and material density maps created by voxelising 3D meshes from segmented phantom STL files. This approach accurately simulates the distinct attenuation characteristics of different materials, closely mimicking real spectral CT conditions. By capturing the variability and complexity of clinical data, gVXR enables the development of AI-driven material decomposition algorithms without the high costs and logistical challenges associated with acquiring large clinical datasets.

2.5. Developing next-generation algorithms for X-ray emission micro-tomography

X-ray emission micro-imaging, whether induced by protons or synchrotron X-rays (SXRF: Synchrotron X-Ray Fluorescence), enables multi-scale mapping of biologically relevant elements, such as minerals and trace metals, with high mass sensitivity [MLJ*22, YFP*19]. In 3D tomography, accurate quantification requires data acquisition over a full 180° angular range. However, practical setups often use 2D sample holders for convenience, resulting in a “missing wedge” at grazing angles. Specialized reconstruction algorithms must be developed to address this limitation. They can be validated using Monte Carlo simulations (e.g. Geant4) [MLJ*22]. Alternatively, gVXR provides a faster deterministic method for generating sinograms from digital phantoms. The microscopic

roundworm *Caenorhabditis elegans* (*C. elegans*), a key model in genetics, aging, neuroscience, and environmental research, has a highly reproducible internal structure, making it well suited for this development. A realistic digital twin incorporating experimental mass density data is being created (see Figure 6). Future work in gVXR aims to model X-ray emission-based micro-tomography, expanding its applicability to techniques like SXRF.

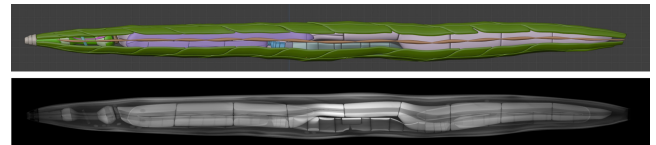


Figure 6: From 3D model to virtual imaging. Top: Computer-Aided Design (CAD) model of the anatomy of *C. elegans*. Bottom: gVXR generated projection image of the phantom.

3. Conclusions

This entry presented gVXR, an open-source framework for simulating X-ray images in real time using GPUs. The method was initially used in medical VR to train image-guided needle puncture. However, the open-source nature of the framework meant that the maintainer “lost control” of what the users might do, enabling collaborations and innovations. gVXR has been used in a number of doctoral theses. We presented here a review of known users’ contributions, including applications in medical VR, medical physics, disease monitoring, and machine learning. Note that gVXR is also used in material science and industrial X-ray imaging. A recent review in X-ray CT, mostly non-clinical, is also available [VAA*24].

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