Developments in Monte Carlo Methods for Medical Imaging

Introduction to Monte Carlo simulations in medical imaging and state-of-the-art computational acceleration methods

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Background

• X-ray imaging is an essential medical tool but is not exempt of ionizing radiation risks
  – Total number of imaging exams increases every year and radiation from different exposures adds up
  – A fraction of patients will develop radiation induced diseases (risk/benefit analysis required)
  – Important to keep the imaging radiation dose “As Low As Reasonably Achievable” (dose/image-quality tradeoff, different situation than radiotherapy)

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• Imaging system design and optimization is an active field of research and innovation
• Ethical and public health reasons strongly limit the non-clinical exposure of humans:
  – Bench testing with objects reproducing anatomical structures (phantoms) is essential
  – Computer simulations are a valuable tool to obtain more information on system performance
    • Advantages: inexpensive, “fast”, repeatable, limited error sources, flexibility in system configuration, measurement of any quantity of interest, ideal detectors
    • Disadvantages: model approximations and omissions limit realism, not warranted to reproduce reality without thorough validation, programming and user error
Simulating x-ray imaging systems

Variable Component to model:
- X-ray source:
  - Energy spectra, filtration
  - Focal spot size, shape
  - Heel effect, off-focus radiation
- Object geometry (anatomy)
  - Quadrics, voxels, triangle-meshes, NURBS (more in following talk!)
- X-ray detector:
  - Image formation model
  - Pixel correlation (MTF)
  - Electronic noise

Known component to model:
- X-ray/atom interaction physics
  - Interaction cross-sections (probabilities) can be obtained from analytical equations or experimental tables
  - Any material of known atomic composition can be modeled with Independent Atom Approximation
- Interactions of interest in 1-100 keV range:
  - Rayleigh (elastic), Compton (inelastic), Photo-electric
  - Not having electric charge, x-ray photons propagate in straight lines and interact sparsely with matter
  - Secondary electrons and fluorescence photons emitted after Compton and photo-electric interactions
  - Electron transport has no impact on projection images and minimal effect on dosimetry at keV energies:
    - Electron range in water at 100 keV = 143 μm, at 10 keV = 2.5 μm

- High-energy particle tracks: 10 MeV electrons (pink) inside 10 cm water slab (Bremsstrahlung photons in yellow)
• Main algorithms used to simulate medical images:

  — **Analytic ray-tracing**
    • Image estimated by computing the probability that x-rays traveling in a straight line from the focal spot to each pixel will not interact with the object (primary image, no scatter)
    • Interaction probability described by exponential attenuation equation with known material attenuation coefficients ($\mu$): 
      $$\text{Prob} \propto e^{-(\mu_1 s_1 + \mu_2 s_2 + \cdots)}$$
    • A geometric algorithm (ray-casting) estimates the path length travelled across each material ($s_i$) in the flight to each pixel
    • Simulation time directly proportional to the number of pixels in the image (and, optionally, to the number of energy levels in the input energy spectrum)

  — **Monte Carlo method**
    • Image estimated by averaging the contribution to each pixel from a large number of individual x-ray tracks
    • X-ray tracks simulated as random walks: random numbers used to sample the initial position, direction and the distance to and kind of the following interaction
    • Differential interaction cross sections used to sample the energy loss and angular deflection following each interaction
    • Simulation time proportional to the number of x rays, which depends on field size and exposure (indirectly to pixel size)
    • Simulated images might display realistic quantum noise statistics if the simulation sampled as many x rays as real acquisitions

• Multiple Monte Carlo codes freely available:
  EGS, GEANT4, MCNP, PENELLOPE…
  — Codes implement different physics and geometry models, have different strengths and weaknesses
  — Consistency among the results from different codes increases reliability of results (see last talk!)

• Monte Carlo simulations may require long computing times and large computing resources:
  — Extremely large number of x-ray tracks to simulate
  — Quantities of interest estimated in small volumes (e.g., dose in voxels, energy fluence in pixels)
  — High resolution phantoms may require lots of memory
• Example Monte Carlo algorithm: PENELLOPE

• Example simulated radiography:
  – $10^7$ primary x rays, 90 kVp
  – Anthropomorphic male phantom from the Virtual Family
    – 305 x 155 x 930 voxels, 2 mm voxels, 8 materials
  – Ideal detector [eV/cm²]:
    » 750x1500, 1 mm pixels

• Common approaches used to speed up simulations:
  – Simplify the implemented physical models to improve the performance at the expense of accuracy or general applicability (e.g., not modeling electrons, Klein-Nishina)
  – Implement variance reduction techniques to optimize the information obtained from each x-ray track without affecting the estimated mean values (*more in next talk!*)
  – Use high-performance computing techniques to execute the same algorithm in less effective time:
    • Optimizing compilation parameters, memory access patterns and instruction scheduling (vectorization) for a specific processor
    • Using parallel execution in multiple processors or accelerators
• Parallel execution in multiple CPUs (Central Processing Units):
  – Use multiple CPU cores in one or many computers (openMP, MPI - Message Passing Interface…)
  – Monte Carlo simulations are embarrassingly parallel: each x-ray track is independent from other
  – Nearly linear speed-up with increasing number of processors (minimal communication overhead)

• Parallel execution in GPUs:
  • A GPU (Graphics Processing Unit) is a massively multi-core co-processor designed to process thousands of concurrent threads
  • Memory handling, cache and execution control simplified to maximize computational power
  • NVIDIA’s GPU architecture (CUDA):

  • Example state-of-the-art GPU:
    NVIDIA GeForce GTX 780
    12 microprocessors with 192 computing cores: 2304 cores
    Clock speed: 0.9 GHz
    Video memory: 3.0 GByte
    
  http://docs.nvidia.com/cuda/cuda-programming-guide

• Multiple GPU-accelerated Monte Carlo codes for diagnostic imaging simulation available:
  MC-GPU, GPRUMCD, gCTD, GMC…
  – Most codes are based on traditional, reliable codes

• Other computational accelerators in development operate similarly to GPUs (massively parallel):
  – Intel Xeon Phi
  – FPGA
Example x-ray Monte Carlo trans. algorithm for GPU: MC-GPU

- 10^{11} x-rays = 65000 blocks of 64 threads, 25000 tracks per thread
- No electrons and no secondary stack
- Virtual interactions to optimize voxel tracing

A. Badal and A. Badano, Accelerating Monte Carlo simulations of photon transport in a voxelized geometry using a massively parallel Graphics Processing Unit, Medical Physics 36, pp. 4878–4880 (2009)
http://code.google.com/p/mcgpu/

Example MC-GPU simulation cone beam CT:
- 1 mm voxels; 540 proj; 2 \cdot 10^{10} x-rays/proj; 65 keV
- Total simulation time: 4.2 days, 90 min/proj/GPU

Figure 1. Voxelized phantom (left), and reconstructed CT images with (center) and without scatter (right).

Figure 2. Eight of 540 GPU-simulated radiographic projections around the phantom (above, primary+scatter; below, scatter only). The gray scales have units of \([\log_{10}]\) eV/cm^{2} per history.

Hybrid computing: parallel execution in CPU+GPU

- Heterogeneous computers are becoming prevalent
- Different parts of an algorithm may scale better in different computational architectures

- Example hybrid Monte Carlo algorithm for the simulation of indirect scintillator detectors: hybridMANTIS
  - X-rays and electrons simulated by PENELOPE
  - Optical photons inside the scintillator modeled by fastDETECT2
  - On-the-fly geometry to reproduce the CsI columnar structure
  - Simulation outputs: Point Spread Function, Modulation Transfer Function, Pulse Height Spectrum, Swank factor.
  - Parallel CPU/GPU execution allows efficient, concurrent x-ray/optical transport.

**hybridMANTIS** algorithm to simulate indirect scintillator detectors. Optical photon transport in GPU runs simultaneously with x-ray, electron transport in CPU.

**Question 1**

One of the main limitations of ray-tracing algorithms used in medical imaging is that they...

- 39% 1. Require too much RAM memory and other expensive computational resources
- 6% 2. Do not intrinsically model scattered radiation
- 22% 3. Can be used only to model simple geometric objects
- 22% 4. Simulate lower resolution images than clinical systems
- 11% 5. Require execution times that are too large for clinical use

**Answer question 1**

- **Answer: 2** – Ray tracing algorithms only model the trajectories of x-rays that do not interact with the objects, scattering events are neglected.

- Computational resources, speed, geometric complexity and resolution are typically not a major limitation for ray-tracing algorithms.

Question 2

GPUs are able to significantly speed up Monte Carlo simulation codes because they...

15% 1. Have much faster access to the main video memory than the CPU to the RAM memory
30% 2. Are programmer-friendly and much easier to program than CPUs
20% 3. Use the Many Integrated Core Architecture with 61 computing cores that work in parallel and communicate at fast speed
35% 4. Have thousands of computing cores that can work in parallel, although some groups of cores have to execute the same instruction each time interval.

Answer question 2

• **Answer: 4** – GPUs have multiple SIMD (Single Instruction Multiple Data) microprocessors that contain hundreds of separate computing cores.
  – Example: NVIDIA GeForce GTX 780: 2304 cores

• Option c describes another useful co-processors accelerator: the **Intel Xeon Phi**

Question 3

Monte Carlo simulation algorithms can reproduce many physical effects that are observed in real CT scans, but one of the following effects is not directly modeled by Monte Carlo transport:

36% 1. Motion blurring
18% 2. Beam hardening
14% 3. Quantum noise
18% 4. Multiple scattering
14% 5. Metal artifacts
Answer question 3

• **Answer:** 1 – Motion blurring caused by heart beat and other time-dependent events does not affect the individual x-ray movement and therefore is not directly modeled by Monte Carlo algorithms. However, multiple simulations with slightly different geometries could be combined to reproduce blurring.

• Metal artifacts such as streaks emerge after the reconstruction of simulated projections because Monte Carlo correctly models photon starvation.