Real-Time Monte-Carlo Path Tracing of Medical Volume Data

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What is Cinematic Rendering?

- A new generation of photorealistic medical visualization based on light transport
- Natural and physically more accurate presentation of medical volume data
The Radiologist’s View of the World
Why do we need photorealism in medical imaging?

Depth Perception

Shape Perception
Why do we need photorealism in medical imaging?
Special Diagnostics

Data by courtesy of:
UMM Universitätsmedizin Mannheim, Germany
Why do we need photorealism in medical imaging?
Surgery Planning
Why do we need photorealism in medical imaging?

Communication
Why do we need photorealism in medical imaging?
Communication

Data by courtesy of:
Dr. Philip Alexander Glemser,
Working group leader Forensic Imaging,
German Cancer Research Center, Heidelberg
Why do we need photorealism in medical imaging?

Education

Credit: Florian Voggeneder

Credit: Magdalena Leitner

Credit: Martin Hieslmair
Cinematic Rendering Video
From X-Ray projection to 3D volume data
From X-Ray projection to 3D volume data

Reconstruction: Computes a 3D X-Ray density volume from many projections

Reconstruction of a slice

Reconstruction of many slices

Volume

Radon-Transformation (Johann Radon, 1917)
Hounsfield, 1971
Algorithmic Steps (for each sample along the rays):
- Compute interpolated density value
- Classification: Density ➔ (R, G, B, alpha)
- Gradient computation, Shading, ...
- Numerical Integration (Combination of R, G, B, and alpha values)
Shading

\[ \nabla f(x) = \begin{pmatrix} \frac{\partial f(x)}{\partial x} \\ \frac{\partial f(x)}{\partial y} \\ \frac{\partial f(x)}{\partial z} \end{pmatrix} \]

- Partial derivative in x-direction
- Partial derivative in y-direction
- Partial derivative in z-direction

ambient
emissive
diffuse

specular
shininess high
shininess low
Ray Casting Results
Physics of light transport

Geometric Optics

Wave Optics

Quantum Optics

Albrecht Dürer
„Underweysung der Messung mit dem Zirckel un Richtscheyt“, 1525

Diffraction
Interference
Polarization
Aberration

Photoelectric Effect
Laser
Maser

Physics of light transport

- Deterministic: Light takes a single path
- Probabilistic: Light can take many paths

Images courtesy of Henrik Wann Jensen, University of California, San Diego, USA
Integral difficult to evaluate:

- Multi-dimensional
  - Sample/scatter positions
  - Light directions
- Non-continuous
  - Highlights
  - Occluders
  - Transfer Function

\[ L(x, \omega) = \int_0^D e^{-\tau(x,x')} \sigma_s(x') \left[ \int_{\Omega_{4\pi}} p(\omega, \omega') L_i(x', \omega') d\omega' \right] dx' \]

\[ \tau(x, x') = \int_x^{x'} \sigma_t(t) dt \]
Monte-Carlo Integration

1 sample per pixel

16 samples per pixel

Riemann

Monte-Carlo
Volumetric Monte-Carlo Path Tracing
Ray Casting vs Path Tracing
How Light Interaction is Modeled in Renderers

Traditional Rendering (single scattering)

Cinematic Rendering (multi scattering)

Improving visualization of noisy (low-dose) CT data using Cinematic Rendering
Camera Model

Thin Lens camera with aperture

Stratified sampling of the detector pixels

Aperture control

Pinhole camera
Camera with aperture
Focal plane on coronaries
Camera with aperture
Focal plane on heart center

Anti-aliasing
Hybrid Scattering

Switch stochastically between surface and volumetric scattering (Kroes 2012)

\[ P_{BRDF} = \alpha_x \cdot \left(1 - e^{-sd \cdot |\nabla s(x)|}\right) \]

\[ h(x, \omega_i, \omega_o) = \begin{cases} h_{BRDF}(x, \omega_i, \omega_o), & \text{if } P_{brdf} > \psi \\ h_{HG}(x, \omega_i, \omega_o), & \text{otherwise} \end{cases} \]
Subsurface scattering
Image-based Lighting

unfiltered

irradiance

reflective
Light Design: Internal Light Sources

functional imaging showing metabolic activity using a positron-emitting radionuclide (tracer)
Tone Mapping

Global operators:
- Exposure function

\[ L_{display}(x, y) := 1 - \exp(-L_{in}(x, y) \times \text{exposure}) \]

- Reinhard’s global operator

\[ L_{display}(x, y) := \frac{L_{in}(x, y)}{1 + L_{in}(x, y)} \]

- Filmic tone mapping: Uncharted 2 operator

\[ L_{display}(x, y) := \text{whitescale} \times \left( \frac{L(x, y) \times (A \times L(x, y) + C \times B) + D \times E)}{L(x, y) \times (A \times L(x, y) + B) + D \times F} - \frac{E}{F} \right) \]

Local operators:
For example: E. Reinhard, M. Stark, P. Shirley and J. Ferwerda, Photographic Tone Reproduction for Digital Images, SIGGRAPH ’02
Phase Functions

Henyey-Greenstein:

\[ G(\varphi, g) = \frac{1 - g^2}{(1 + g^2 - 2g \cos \varphi)^{3/2}} \]


Fogbow + Glory

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Transparent hulls

Foil  Ice  Water  Glass

Schlick approximation
Scalable architecture leveraging distributed multi-GPU OpenGL rendering

• **Rendering Context**
  - Manages the resources and rendering algorithms for a single GPU in a rendering node

• **Raycasting Core**
  - Rendering core component, GLSL shader

• **Display Context**
  - Manages the rendering results of local Rendering Contexts (GPU-to-GPU memory transfer (NV_copy_image), compositing, rescaling, tone-mapping, etc.)
  - May share a GPU with a Rendering Context or run on dedicated low-power GPU
  - Image capture and video streaming for remote viewing applications
  - GPU-based compositing and tone-mapping, fast image capture using NVIDIA Inband Frame Readback (IFR) with 4:2:0 chroma subsampling
  - Very low latency/bandwidth streaming for remote interaction applications

![Diagram of rendering architecture](image-url)
Mobile Cinematic Rendering

- Cloud-based Rendering Server, iOS client
- iOS native renderer (iPad Air 2/iPhone6)
- Android native renderer (Tegra K1)
- iWatch from cloud or iPhone (30 fps)
Computational Load (GTX 980, data: 512x512x1699@16bit, 1920x1080)

Interactive quality (10 it)
After 2 seconds (100 it)
After 10 seconds (500 it)

- total rays: 20,736,000
- total paths: 14,024,580
- total scatter events: 41,064,594
- total light lookups: 34,397,030
- total gradients: 27,230,231
- total sample events: 1,687,624,300
- total classification events: 1,503,524,423

- total rays: 207,360,000
- total paths: 138,562,408
- total scatter events: 442,808,953
- total light lookups: 365,000,004
- total gradients: 224,830,809
- total sample events: 16,769,200,328
- total classification events: 15,213,027,095

- total rays: 1,036,800,000
- total paths: 689,463,816
- total scatter events: 2,189,449,922
- total light lookups: 1,805,740,978
- total gradients: 1,130,386,976
- total sample events: 84,105,247,524
- total classification events: 76,286,984,974

- total rays: 20,736,000
- total paths: 17,975,530
- total scatter events: 54,965,441
- total light lookups: 24,426,885
- total gradients: 44,807,988
- total sample events: 943,121,939
- total classification events: 653,538,011

- total rays: 207,360,000
- total paths: 173,973,381
- total scatter events: 563,696,623
- total light lookups: 313,506,260
- total gradients: 384,046,705
- total sample events: 10,798,965,836
- total classification events: 8,287,325,606

- total rays: 1,036,800,000
- total paths: 862,863,830
- total scatter events: 2,786,035,042
- total light lookups: 1,549,583,536
- total gradients: 1,896,305,376
- total sample events: 53,563,338,027
- total classification events: 41,148,705,771
Application: Artificial Heart Valve

Data courtesy of Dr. Ricardo Budde - Erasmus Medical Center, Rotterdam
Application: Gout visualization by urat detection using Dual-Source CT
Application: Cinematic Rendering of CT Vascular Head

Courtesy of Israelitisches Krankenhaus, Hamburg, Germany
Application: Magnetom 7T Knee

Data by courtesy of:
Dr. S. Trattnig, Medizinische Universität Wien, Austria
Application: MR brain with DTI Fibers

MR data courtesy of:
Max Planck Institute, Leipzig, Germany
Application: Cinematic Rendering of MR 7T Brain
Data by courtesy of:
Dr. Philip Alexander Glemser,
Working group leader Forensic Imaging,
German Cancer Research Center, Heidelberg
Deep Space 8k, Ars Electronica Center, Linz, Austria

- Museum of the future: Intersection of arts, technology, society
- 16x9 meters wall and floor projections, 8192x4320 pixels each, >70 MP active stereo, 120 Hz
- 8 Christie Boxer 4k30 Mirage: 30,000 lumen, 3DLP, 4K projector at 120Hz, 4096x2160 px, shutter glasses
- 2 XI-MACHINES, each with four NVIDIA Quadro M6000, NVIDIA Mosaic technology

Credit: Martin Hieslmair

Photo: Stadt Linz

2.691.367.920.768 tri-linearly interpolated samples
Prof. Dr. Franz Fellner
Director of Radiology at Linz General Hospital

"Anatomy of the Dead ➔ Anatomy of the Living"
Conclusions

- Siemens is pioneering the use of NVIDIA GPUs to bring **heavy computationally** dependent ray/path tracing to medical visualization
- Applications in special **diagnostics, surgery planning, communication** and **education**
- Photorealistic/Hyperrealistic images lead to **democratization of medical imaging**
Thank you for your Attention! Questions?

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