Scatter Correction for Industrial Cone-Beam Computed Tomography (CBCT) Using 3D VSHARP, a fast GPU-Based Linear Boltzmann Transport Equation Solver

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February 13, 2019

Keywords: Cone-Beam Computed Tomography (CBCT), Scatter Correction, Finite-Element Boltzmann Transport Equation Solver
• Goal: Improve Industrial Cone-beam CT image quality with software-based scatter correction

• Methods:
  • Deterministic X-ray transport scatter correction algorithm
  • Monte Carlo validation
  • 450kVp experiments

• Results:
  • Aluminum motorcycle head
  • Inconel turbine blade
Overview: What Problem Are We Solving?

- Scatter Fractions of 80% typical
- Scatter-Related CBCT Artifacts:
  - Cloudiness
  - Poor boundary definition
  - Non-uniform CT Units
  - Compromised automated analysis
- Other Correction Methods:
  - Hardware – Extra scan time, inconvenient
  - Deconvolution – Less accurate for industrial parts [1]
  - Machine Learning – Lots of training, heuristic [2]
  - Monte Carlo – Very slow

Uncorrected Scatter Leads to Poor Reconstructions

Inconel Turbine Blade:
- Poor concave surface definition

Aluminum Motor Head:
- Hollow regions incorrectly filled with material
- Missing surfaces
Reconstructions Performed Using Varex’s Cone Beam Software Tool (CST) Set

- **Features**
  - Geometry calibration
  - Plugins with flexible pipeline for rapid development
  - Pick and choose corrections:
    - Lag - 2D-Scatter - Beam Hardening - Detector Blur - Metal Artifacts
    - and more.
  - Filtered backprojection (CPU and GPU)
  - Iterative reconstruction (GPU)
  - C#, C++, and other .NET languages
Methods

• 3D VSHARP is an in-development scatter correction
  • Part 1: Solve Primary
  • Part 2: Solve Scatter - Deterministic finite element solution of the Linear Boltzmann Transport Equation
  • Part 3: Calculate Scatter Fraction

• Expected Beta-release end of year

• Monte Carlo Validation
FAST GPU-Based X-Ray Transport Solver
Part 1 – Primary

1. Solve Primary Transport: Ray-trace primary to detector
   • First pass FDK or CAD

   **Beer/Lambert Law:**
   \[ I(E) = I_0(E) e^{-\mu(E)x} \]

1) Trace photons from source to all voxels in the object.
FAST GPU-Based X-Ray Transport Solver
Part 2 – Scatter

2. Finite Element Solver: Linear Boltzmann Transport Equation (LBTE)

1) Trace photons from source to all voxels in the object.

2) Deterministic solver scatters photons inside the object.

\[
\hat{\Omega} \cdot \vec{\nabla} \phi_E(\vec{r}, E, \hat{\Omega}) + \mu_t(\vec{r}, E) \phi_E(\vec{r}, E, \hat{\Omega}) = S(\vec{r}, E, \hat{\Omega}) + \int_0^{E_0} dE' \int_{4\pi} d\Omega' \left[ \mu_s(\vec{r}, E' \rightarrow E, \hat{\Omega}' \rightarrow \hat{\Omega}) \phi_E(\vec{r}, E', \hat{\Omega}') \right]
\]

3) Trace scatter flux from all voxels to each detector pixel.
Motorcycle Head Scatter Fraction Estimates Exceed 80%

Scatter Fraction = \frac{\text{Scatter}}{\text{Scatter} + \text{Primary}}
VSHARP Accuracy Matches Monte Carlo Accuracy

Processing Time

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<tr>
<th></th>
<th>MCNP</th>
<th>3D VSHARP</th>
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<td>$10^6$ CPU-sec, $10^{10}$ γ</td>
<td>1 GPU-sec</td>
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SF = \frac{SCT}{PRI + SCT}

Scatter Fractions (SF) - 450 kVp

Aluminum Box: Al & Inconel Inserts

Source

14 cm

Inconel

Al

24 cm
CBCT Image Acquisition and Pre-Processing

- 1620-AN3 Amorphous-Si Panel
- 41x41 cm² area, 200μm pixels
- 450 kVp, 2 mA, 3 fps
- 720 projections, SAD:106, SID:127.5cm

Detector Response and Source Shape characterized
**3D VSHARP™ – Reconstruction with CST**

**Pre-Processed Projections** → **1st Pass FDK Image (Low Res)** → **X-Ray Transport** → **Subtract Scatter From Pre-Processed Projections** → **Result: 2nd Pass FDK Image (High Res)**

**Varex Cone Beam Software Tools (CST)**

- **PRIMARY**
- **SCATTER**
Improved Image Quality – Aluminum Motorcycle Head

- Reduced cloudiness
- Improved wall definition
- Improved material separation in histogram
Improved Surface Rendering: Aluminum Motorcycle Head
Aluminum Motorcycle Head
Improved CT Units – Inconel Turbine Blade

- Improved concave wall definition
- Wall blur reduced from 5mm to 2mm
- Better Inconel/Air discrimination
- 30% less variability

Line Profile - Inconel Turbine Blade

- Uncorrected Inconel
- 3DVSHARP Inconel
Inconel Turbine Blade

CORRECTED

UN-CORRECTED
Conclusion & Next Steps

Conclusion:

• 3D VSHARP’s physics-based scatter correction produces more accurate reconstructions with improved material boundary discrimination

• Scatter estimates with Monte Carlo-like accuracy in 1-millionth the time

• No extra hardware, empirical calibration, or additional scan time

Next Steps:

• Fully integrate 3D VSHARP into CST’s Software Toolset

• Add additional options for more materials, X-ray sources, and detectors

• Multi-material Scatter Correction
References


[8] MCNP6.1, Los Alamos National Laboratory, New Mexico, USA.
