Quantitative and Qualitative Approaches to Neutron Imaging

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Summary and Conclusions

• Neutron imaging and X-ray CT similar/complementary

• Presence of fissile material can be quantified using non-traditional / low resolution imaging geometry

• Standard tomographic techniques allow quantitative high-resolution imaging of hydrogenous material

• Coded source based data acquisition facilitates higher resolution imaging without loss of much needed flux

• Can be combined with X-ray CT, SPECT (not shown)
Neutron vs X-ray Imaging

Macroscopic cross-section, Beer’s Law:

\[ \Sigma = N \frac{N_A}{M} \rho \text{ [cm}^{-1}] \]

\[ I_1 = I_0 \exp(-\int L \, dl \, \Sigma) \]

N: atomic number, \( N_A \): Avagadro’s number
M: molar mass, \( \rho \): material density

http://www.psi.ch/niag/what-is-neutron-imaging
D.C. Hensley, ORNL/NorthWest Nuclear LLC

- Non-destructive assay, examination of waste drums
- Passive: single (α,n) reactions, correlated events
- Active: pulsed thermal neutrons, differential dieaway

- Imaging equations: \( y = E \cdot m \)
  
  Single: \( y_{d\theta} = \sum_v e_{d\theta v} \cdot m_v \)
  
  Corr.: \( y_{d\theta} = \sum_v e_{\theta v} \cdot e_{d\theta v} \cdot m_v \)
  
  Active: \( y_{d\theta} = \sum_v e_{d\theta v} \cdot f_{\theta vt} \cdot m_v + h_{dt} \)

\( y = \text{yield}, e = \text{detector efficiency}, m = \text{mass}, f = \text{flux} \)
\( d = \text{detector pack}, v = \text{voxel}, \theta = \text{rotation angle}, t = \text{time} \)
APNEA 2: Least Squares Formulation

- LSQR used to solve penalized least squares problem
  \[ m = \arg \min_\mathbf{m} \| \mathbf{E} \mathbf{m} - \mathbf{y} \|^2 + \sum \beta_i \| \mathbf{H}_i \mathbf{m} - \mathbf{z}_i \|^2 \]
- Concentrated vs uniformly distributed source material
- Drum model (image)
• $^{252}$Cf point source embedded in soil: true rate 9,555 n/s

Location: $r=0''$ (core)

Total activity = $9478.1$
Min, max levels = 0.0   9345.0

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Location: $r=6''$ vs 0,8'' for model

Total activity = $8210.0$
Min, max levels = 0.0   5962.4

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APNEA 4: Example Results

- D&D waste from Nuclear Fuel Services (Erwin, TN)
- $^{240}$Pu embedded in soil – sample size of 528 drums
HFIR 1: Tomographic Imaging

T. Toops and C. Finney, ORNL / NTRC

- CG-1D beamline at High-Flux Isotope Reactor (HFIR)
- High-resolution cone beam tomography (proj. based)
- SIRT used to solve weighted least squares problem
  \[ x = \arg\min \| A x - b \|_w^2 + \beta \| x \|_2^2 \]

CCD array: 2048 x 2048
Angular incr.: < 1°
Exposure time: 30-240s
Angular range: 180° + fan
Image resolution: 40 um
• Diesel particulate filter (DPF) traps soot, particulate matter
• Quantify deposit / regeneration

Cross-sectional image

• Differences in inlet and outlet channel open areas correlate with average deposit build-up

May 7, 2014
Jens Gregor, University of Tennessee
P. Bingham and H. Santos-Villalobos, ORNL

- HFIR guide set-up leads to near-parallel neutron beam
- System design trade-off: flux $\alpha D$, resolution $\alpha L/D$, $1/d$
Coded Source 2: Mask Aperture

- Detector resolution limit overcome thru magnification
- Small pinhole = resolution, many pinholes = more flux
- Overlapped projections → radiographic reconstruction

Beam Mask Object Scintillator

≈ 0.0 m L=1.0m D=5.0m
Coded Source 3: Example Results

Mask

Projection

SIRT N=1000

CGSIRT N=4

200um / 1.3K

50um / 24.6K
Code Source 4: Example Results

- Convolution reconstruction of metal screw: HFIR data

Direct imaging at top. Coded source at bottom.

- Iterative reconstruction of wedge: simulated

100um  50um  20um  10um

SIRT N=100  CGSIRT N=4
Related Imaging Research Examples

Medical, preclinical imaging
PET, uSPECT, uCT, MRI, Monte Carlo

Industrial, security imaging
Neutron and x-ray CT

- Statistical, algebraic reconstruction algorithms and Feldkamp
- Academic proof-of-principle and commercial/production code
- Participant: ALERT T03 Iterative Recon, T04 ATR Development