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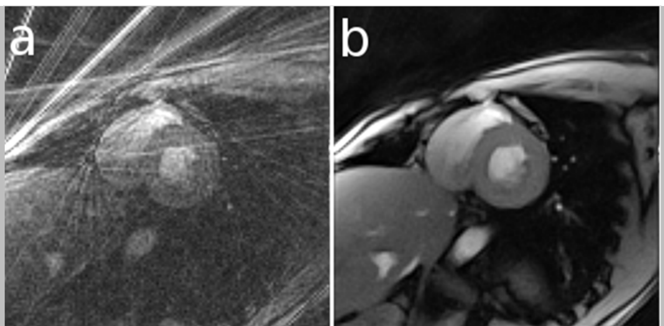

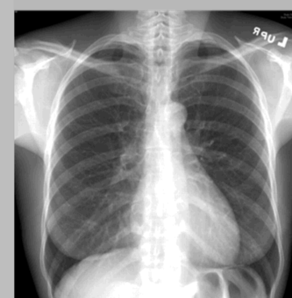

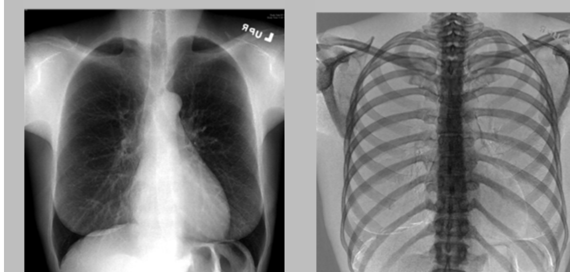

Big-Data Multi-Energy Iterative Volumetric Reconstruction Methods for As-Built Validation & Verification Applications

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Project Objective

- Create an advanced diagnostics tool to identify slight nuances of as-built components.
  - Deviations from ideal can result in large changes leading to different outcomes for simulated chaotic systems.
  - Quantify uncertainty and quality in manufacturing and simulation

- Currently, X-ray Computed Tomography (CT) is used for Non-Destructive Evaluation
  - Not ideal, various types of artifacts
  - Artifacts located exactly at regions of interest (interfaces, material boundaries, etc.)
  - CT datasets are hand segmented and imported into simulation tools.
  - Big Data for input and output (Typically ~12GB-4TB input and output)

- Solution: Multi-Energy Iterative Reconstruction (MEIR)
  - Energy resolved iterative reconstruction for CT
  - Greatly reduce artifacts and noise in volumetric reconstruction.
  - Investigate techniques that combine innovative detector technology with intelligent data science approaches.
  - Very Big-Data (~25GB-100TB input and output)

Why Sandia?

- Directly addresses Engineering Science Research Foundation (ESRF) Call
  - Novel diagnostics for experimental discovery and validation.

- Indirectly addresses ESRF Call
  - Enabling Digital Image Correlation large-scale deformation.
  - Elucidating mixing and reaction process at device-relevant conditions.
  - Understand and develop predictive models based on diagnostic data.

- Directly addresses Engineering of Materials' Reliability Research Challenge
  - Provide more accurate and faster Non-Destructive Testing (NDT) to characterize materials reliability.
  - Impact understanding of interfaces, environmental effects, and nucleation.
  - Applies to focal areas (energy storage, sensor, encapsulants, metals, and energetic materials).
  - On pace for 3x faster predictability by 2025.

Why now? Why this Project?

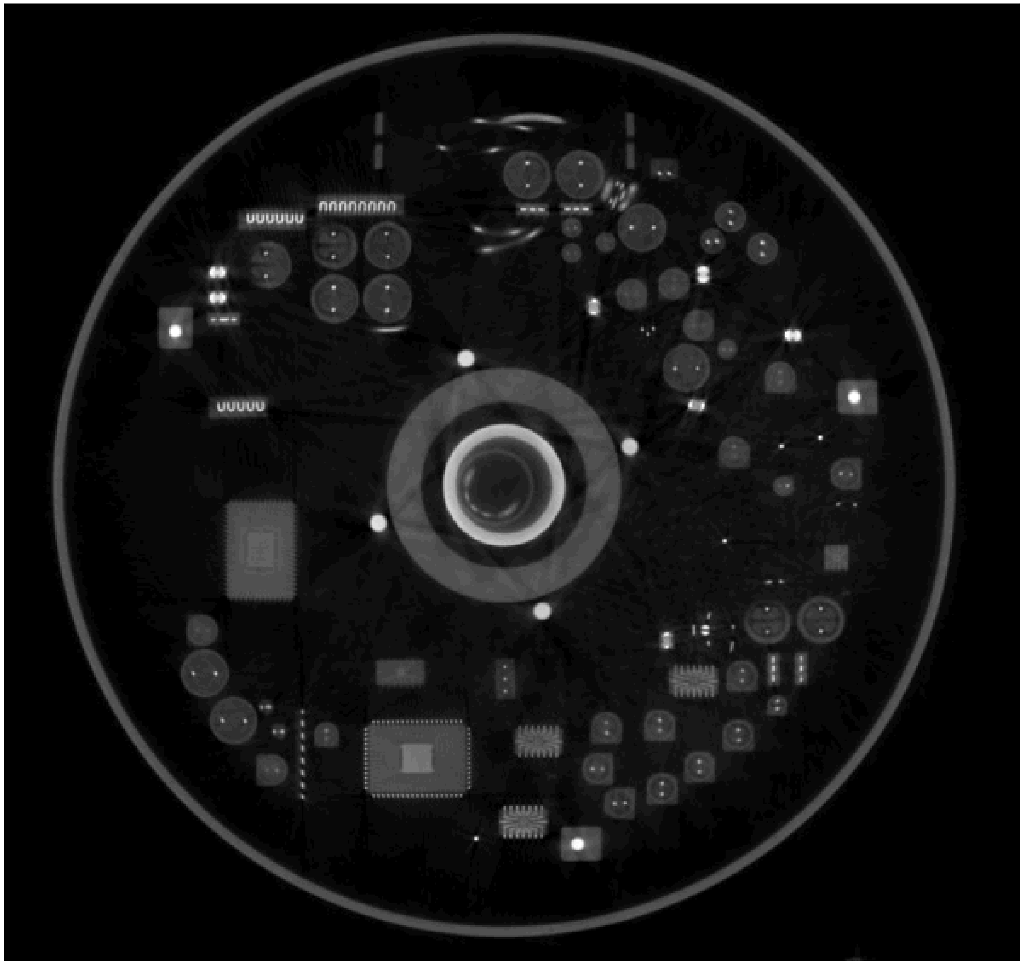
- CT limitations have been reached.
  - SNL has a growing and urgent need beyond those limitations.
    - Component inspection, materials testing, advanced components testing, etc.
    - Potential components could include: Neutron Generators, Detonators, Thermal Batteries, etc.
    - Limitations due to penetrating power, resolution, magnification, etc.

- Iterative Reconstruction
  - MEIR has never been attempted at non-medical scale.
    - Medical Scale: 1 – 6 Gigabytes
    - SNL Scale: 12 Gigabytes to 4 Terabytes (each input AND output)
  - Avoided due to immense acquisition and post-processing.
    - How do we handle such large amount of data?!

- Proposed experimental acquisition
  - Leverage nascent technology and scanning techniques.
  - Very high risk, has never been attempted for this application.

- If successful, then SNL can transform many areas.
  - NDT, big-data sciences, advanced diagnostics, information science, and SNL's world class radiography capabilities.

CT Artifacts



Consequences of using bad data

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Goals and Success

- Deliver generalizable Scientific Big-Data Approaches
  - Intelligently and efficiently manage 100s of terabytes of data for numeric processing.
  - Optimize information flow through scalable data reuse and transfer minimization

- Deliver optimized advanced diagnostics tool
  - Capable of reconstructing SNL relevant engineering big data.

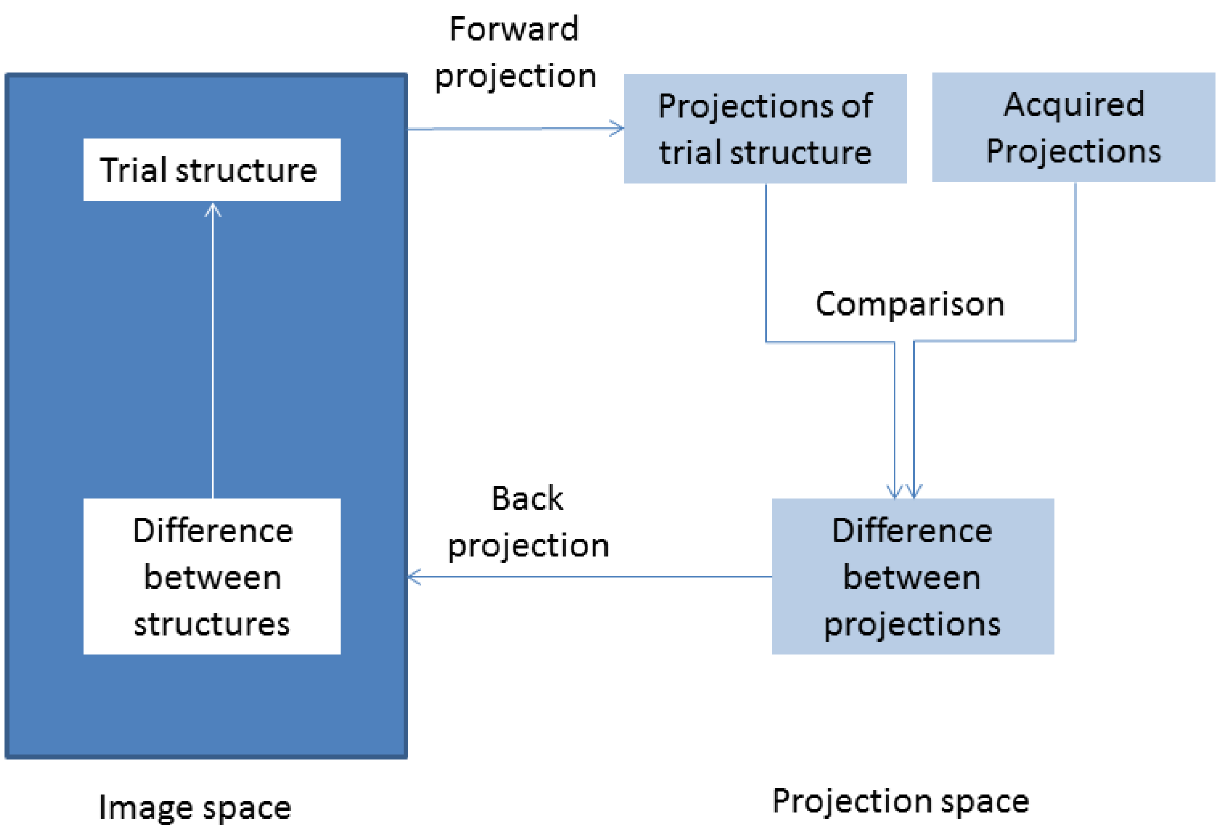
- Deliver a big data optimized semi-autonomous volumetric segmentation algorithm with suitable importation to SIERRA/CTH.
  - Fairly well studied for CT reconstructions (low risk).

- Develop novel X-ray sampling techniques to supplement MEIR.

- Peer-Reviewed scientific publications, conferences, Intellectual Property (IP), and requisite SAND reports.
  - Technology advance submitted (SD#13598) under SNL IP attorney guidance.

MEIR (Iterative Reconstruction)

- Iterative algorithms:
  - Iteratively changing a trial structure until its projections are consistent with the original projections of the unknown structure.
  - Typically an iterative sequence of forward and back projection with constraints.



Based on diagram from http://radiologykey.com/basic-principles-2/

MEIR (Iterative Reconstruction)

- Many candidate algorithms for MEIR exist
  - Our first investigation revolves around Landweber-type algorithms

$$\hat{\mathbf{f}}^{k+1} = \hat{\mathbf{f}}^{k} + \mathbf{H}^{\dagger}\left[\mathbf{g} - \mathbf{H}\hat{\mathbf{f}}^{\mathbf{k}}\right]$$

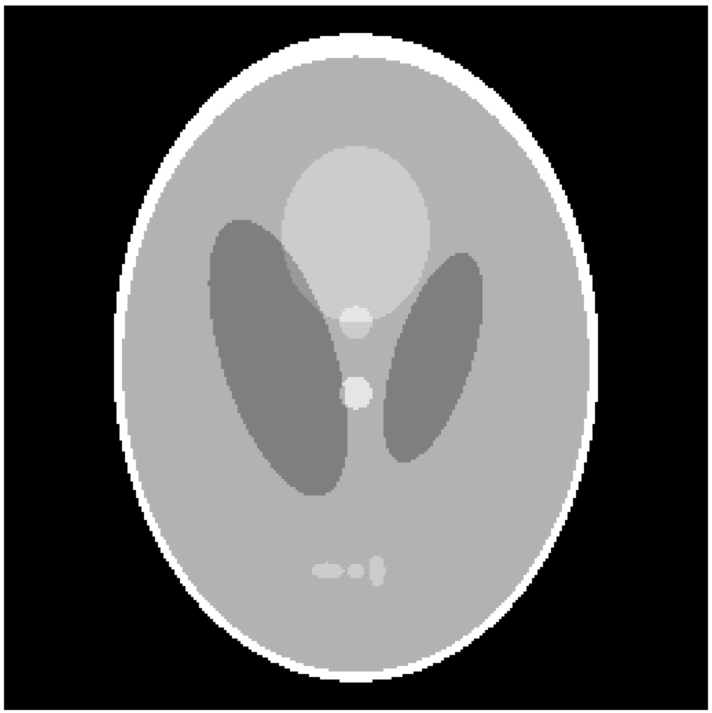
- If successful, this algorithm will reduce artifacts due to
  - Beam hardening around edges and interfaces
  - Sparse sampling/Incomplete Data

- Can be used on traditional datasets or multi-energy datasets.

- Risk: Very computationally intense and data intense problem.
  - Traditional single energy Reconstruction on Big Data: 1 hour to 3 days
  - Iterative energy resolved big data (theoretical): 10 hours to 300 days!

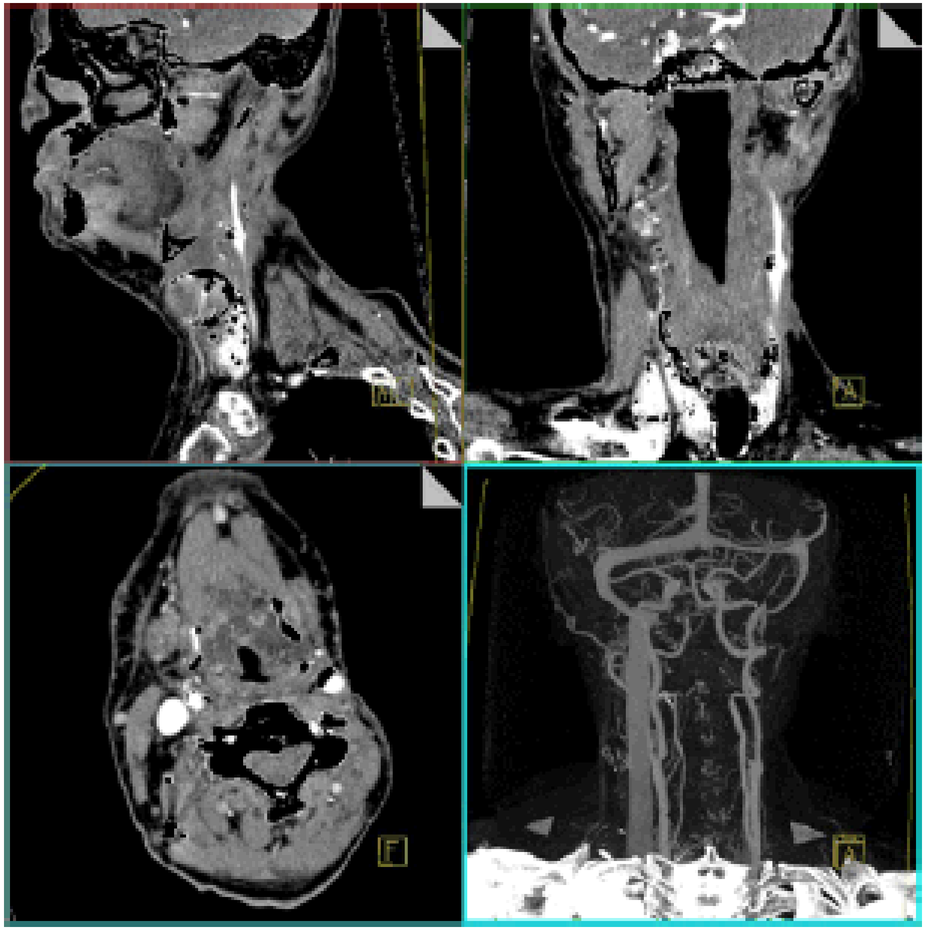
Iterative Reconstruction

Original Object



MEIR Continued (Multi-Energy)

- Multi-energy approaches (including dual energy) require several scans at different energies.
- Medical examples of segmentation tasks include bone-removal to study neighboring soft tissue. Bone/plaque removal, leaving only contrast agent (iodine). M. Riedel
- Limitation: Several scans with good register/alignment necessary.



CT view of lower cranial, neck, upper torso

Previous Exploratory Work

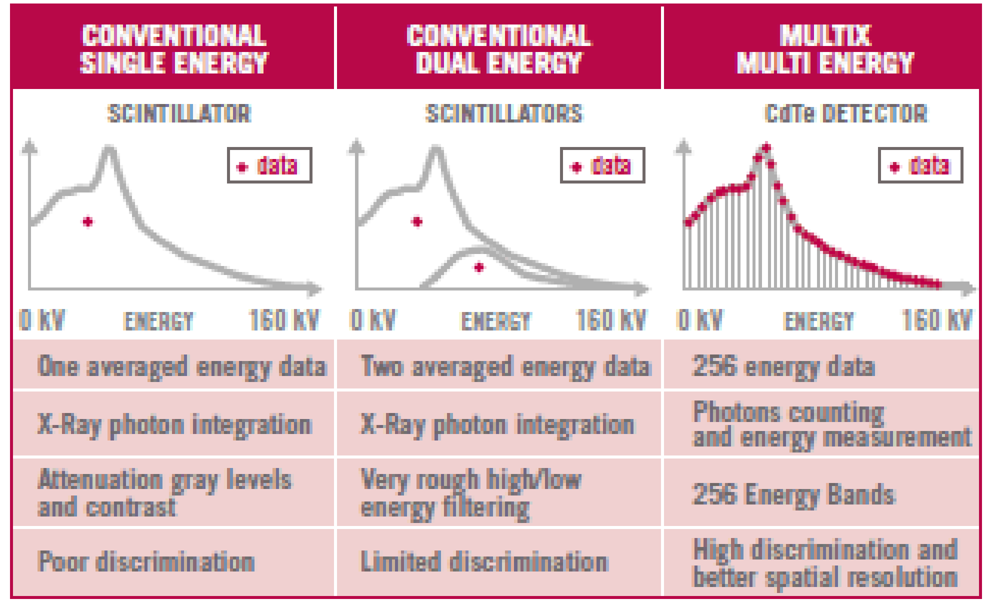
- Previous work explored feasibility of big-data forward projection.

- This work explored a small-volume forward projection using a single Graphics Processing Unit (GPU)
  - Used both Gaming GPUs (Fermi-Class GTX 590) and Scientific Computing GPUs (Fermi-Class Tesla M2090).
  - Exhibit similar irregular properties to that of backprojection
    - Similar approaches will be leveraged in forward projection
    - Memory access pattern starts well, degrades quickly
  - Multi-GPU partitioning may be difficult due to large data transfers
    - Dynamic partitioning and asynchronous transfers
    - Partial volume uploads/High data reuse.
  - Tri-linear interpolation increases the complexity compared to backprojection.

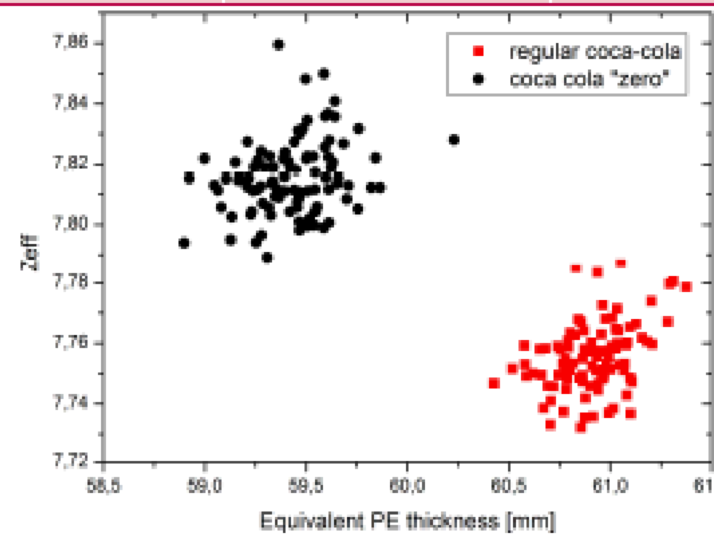
- To mitigate computational risk, we will leverage GPUs on a modest cluster.
  - Iterative methods will require multiple forward/back projections for each energy bin.

The Power of Energy Resolved Imaging

- Virtually mono-energetic energies.
  - Results in cleaner data for analysis and segmentation.
- Increase Signal-to-Noise Ratio
  - Dependent on corresponding K-edge
- Single scan for multi-energy data!
  - Reduce dose and scan time
- High Risk: Very new technology;
  - Large payoff for many engineering, science, and security applications that could significantly evolve each area.



CONVENTIONAL SINGLE ENERGY	CONVENTIONAL DUAL ENERGY	MULTIX MULTI ENERGY
SCINTILLATOR	SCINTILLATORS	CdTe DETECTOR
0 kV ENERGY 160 kV	0 kV ENERGY 160 kV	0 kV ENERGY 160 kV
One averaged energy data	Two averaged energy data	256 energy data
X-Ray photon integration	X-Ray photon integration	Photons counting and energy measurement
Attenuation gray levels and contrast	Very rough high/low energy filtering	256 Energy Bands
Poor discrimination	Limited discrimination	High discrimination and better spatial resolution



Figures from Multix Detector Documentation

Parallel Efforts

- This work contains two main efforts
  - Algorithm R&D (Big-Data processing)
  - Experimental acquisition techniques (Big-Data acquisition)

- Neither effort is completely dependent on the other; however much synergy exists.
  - If Algorithms effort failed: Multi-Energy acquired datasets can still leverage the traditional multi-energy direct reconstruction.
  - If Experimental effort fails: The algorithms can still leverage traditionally acquired dual and multi-energy datasets.

- Algorithmic efforts will start with traditional dual-energy datasets which can be easily acquired with existing SNL hardware.
  - Mitigates risk
  - Algorithmic work won’t be delayed by slips from the experimental effort.

Stretch Goal 1: Software Deliverable

- If successful, we envision that late in the project we would like to develop an alpha/beta level release of a reconstruction tool that can be used by x-ray technicians
  - Improve usability
  - Deployment into target populations
  - Advertising
- Although Sandia Challenges are the main motivators; this technology has widespread application beyond SNL such as industrial manufacturing, national labs complex, security inspection, etc.
  - A usable tool will improve return on investment (software purchasing, licensing, etc.)
  - Improves SNL's visibility in the scientific community
- This goal would depend on the success of the algorithm investigation.

Stretch Goal 2: Portability

- There is no standard computational platform for CT reconstruction.
- Although Big Data and High Performance Computing architectures are the main focus; every effort will be made to allow for this algorithm to function within reason on a wide range of computational hardware.
  - hetero- and homogeneous clusters , Tablets, desktops, workstations, servers.
  - Including small-scale platforms will increase the prevalence of the algorithm.
- We would be interested in testing this algorithm on very large systems such as Titan at Oak Ridge National Laboratory.
  - Unclassified input should be feasible.
  - Will inquire with Investment Area Team (IAT) and relevant parties on feasibility

Current Status

- Algorithm work: Big-Data backprojection algorithm is complete and testing will begin soon. Forward projection algorithm is currently in development.

- Experimental work: Energy discriminating detector has arrived, detector housing is complete. Initial test images will be acquired as soon as radiation shielding and electrical lines have been installed.

Thank you

- Our team appreciates the opportunity to present our work.
- Questions?