Coding for X-ray Diffraction Imaging

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Goal: detect presence of threat substances in carry-on baggage

Primary constraints/challenges:
- Fast scan time (< 5s/bag) for high throughput
- Good specificity and sensitivity to broaden threat space and reduce false alarm rate

Approach: compressively acquire and combine transmission and coherent scatter signals to obtain material-specific signature at each voxel

Results: structured illumination + energy-sensitive detection make real-time imaging possible
Background
Coherent x-ray scatter

Bragg’s law

\[ q = \frac{E}{hc} \sin \left( \frac{\theta}{2} \right) \]

- \( q = \frac{1}{2d} \): momentum transfer
- \( \theta \): scatter angle
- \( E \): x-ray energy

Differential cross section

\[
\frac{d}{d} \propto \left[ 1 + \cos^2 \theta \right] f(q, r)
\]

- \( f(q, r) \): position-dependent form factor

[Graph showing Bragg's law and differential cross section for H₂O and Al powder]
Techniques to measure $f(q)$

**Angle-dispersive**
- Study $\theta$ dependence of scatter for fixed $E$

**Energy-dispersive**
- Study energy dependence of scatter for fixed $\theta$

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Coherent scatter imaging

Coherent scatter computed tomography (CSCT)

- Rotate/translate object
- Multiplexed
- State of the art: several minutes/2D slice

Angew. Chem. Int. Ed. 50, 10148 (2011)
Dicken et al., Opt Exp. Vol 19, 6406 (2011)
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Primary challenges:
- scatter rates are small
- attenuation effects are important
Poor photon efficiency $\rightarrow$ slow scan times

Kinetic Depth Effect X-ray diffraction (KDEXRD)
- Move detector
- Multiplexed
- State of the art: 10 min/voxel

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Speeding things up

- Increase incident x-ray flux
  - more current
  - less filtering
- Use multiple beams
  - in series
  - in parallel (non-multiplexed)
  - in parallel (multiplexed)
- Focus scatter
  - multiple sources
  - shaped sources

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Coded aperture x-ray scatter imaging (CAXSI)
Pencil beam coded aperture x-ray scatter imaging (CAXSI)

- Angle-dispersive
- Use “narrowband” source
- Use mask to triangulate scatter origin in range
- Snapshot acquisition

MacCabe et al., Opt. Exp. 20, 16310 (2012)
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Imaging results

Resolution:
\[ \Delta z = 30 \text{ mm} \]
\[ \Delta q = 0.1 \text{ nm}^{-1} \]

MacCabe et al., Opt. Exp. 20, 16310 (2012)
Snapshot fan-beam tomography

Extend results to fan-beam geometry
- Get range, cross-range, and angular scattering profile

DUKE letters (plastic)
Single snapshot

Multi-shot fan-beam tomography

Toy army man
(3 spatial + 1 material)

Ticking clock
(2 spatial + 1 temporal + 1 material)

Coded aperture coherent scatter spectral imaging (CACSSI)
Broadband illumination

Monochromatic source

- Many photons thrown away
- Specific detector locations required

- Use all incident photons
- Range of available detector locations

J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013)
Pencil beam geometry

- Object
- X-ray pencil beam
- Coherent scatter
- Coded aperture
- Energy-sensitive detectors

J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013) [under review]
**Simulation**

**Experiment**

**Raw measurements**

Bragg’s law

\[ x = \frac{2 \hbar c q z}{E} \]

Coded aperture

\[ I_s \approx t[x(1-d/z)] \]

J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013) [under review]
Single object reconstruction

HDPE at z=252 mm

Converting to correlation map

J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013)
Multi-object reconstruction

\[ f_{\text{est}} \quad f_{\text{truth}} \]

C at \( z = 237 \)

NaCl at 267

J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013)
Water-like object discrimination

Different concentrations of H\textsubscript{2}O + Methanol

H\textsubscript{2}O + vs 50% H\textsubscript{2}O\textsubscript{2}

J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013) [under review]
CACSSI resolution

Predictions

Δ [ ]

Δ [ / ]

Δ [ / ]

Observations

Δz~5 mm with
Δq<0.02 1/Å

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Dependence on mAs

Only ~100 mAs required to identify a range of materials with < 1% of total scatter signal collected

\[ \text{corr.} = \frac{f \times f_{\text{est}}}{\|f\| \cdot \|f_{\text{est}}\|} \]

\[ \phi(\cdot) = \cos^{-1} \left( \frac{g_{\text{max}(mAs)} \times g_{mAs}}{\left| g_{\text{max}(mAs)} \right| \left| g_{mAs} \right|} \right) \]
Lingering issues

• Bulky
  – Detectors should be object thickness away from mask

• Difficult to scale to full 4D data cube
  – hard to code all dimensions
  – need higher-dimensional detector arrays ($)

• Bottom line: still too slow
  – Need more efficient use of source photons
Structured illumination coherent scatter imaging (SICSI)
Structured illumination

Measurement strategy

• Use code to modulate illumination before object
• Object moves through beams
• Acquire many spectra at different times using energy-sensitive pixels: \( g(E, t, x, y) \)

J. A. Greenberg et al., Structured illumination for tomographic molecular imaging (2013) [under review]
Structured illumination

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Advantages

- Optimal use of source photons (no spectral/minimal spatial filtering)
- Scales easily up to 4D
- Fewer detectors needed (sparse array only)
- Allows for simultaneous tomosynthesis
- Compatible with multiple sources
- Allows for adaptive implementation
- Simple modification to existing machines:
  - Open up collimation
  - Add scatter detectors
Example: modulated fan beam

- **Source**: conventional x-ray tube
- **Mask**: periodic series of holes along a line \( t(x) = (1+\text{sign}[\sin(u x)])/2 \)
- **Detector**: Single, energy sensitive sensitive pixel

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SICSI experiment

Source/collimation (125 keV)

mask

(moving) object

detector

• 3 mm thick Pb
• 1.5 mm diameter holes
• 3 mm center-to-center spacing

Mask (x-ray image)

J. A. Greenberg et al., Structured illumination for tomographic molecular imaging (2013) [under review]
Single object reconstruction

Al powder at z=640 mm, x=-3 mm

J. A. Greenberg et al., Structured illumination for tomographic molecular imaging (2013) [under review]
Multi-object classification

Graphite at x=-3, z=613

Teflon at x=5, z=593

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Dependence on mAs

*Notes*
- Only use 1 pixel
  - Collect ≈0.1% of scatter!
- Accurate results down to 5 mAs (defined per integration time)
  - Corresponds to ~1 cm/s belt speed with 10 mA source

Going forward
- Use more pixels
  - Collect more photons (e.g., 10-100x)
  - Better conditioning (less compressive)
- Use higher mA/kV source (e.g., 160 kV at 90 mA)
- Combine with transmission-based tomosynthesis
- Use full cone beam

Real-time (>10 cm/s) operation with real suitcases
Summary

• Arrays of energy-sensitive detectors are crucial for real-time operation

• Minimal source filtering with structured illumination yields a drastic speed-up in required imaging time

• Integration of scatter and transmission is necessary

• Prototype construction is currently underway!
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