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Topology-Guided Volume Fusion for Multi-Energy Spectral Computed Tomography

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Problem Statement

Fuse multi-energy CT volumes into a single representative field.

Enable topology-aware dimensionality reduction for spectral CT data.

Preserve key features across channels for improved rendering and analysis.

Motivation

Photon-Counting CT (PCCT) captures rich spectral details beyond standard CT workflows [Flohr 2023].

Multiple co-registered volumes add redundancy and complicate visualization, where standard transfer functions (TF) prove ineffective.

Fused volume that preserves features across energies is needed.

Topology-guided fusion retains meaningful structure, improving tissue differentiation and analysis.

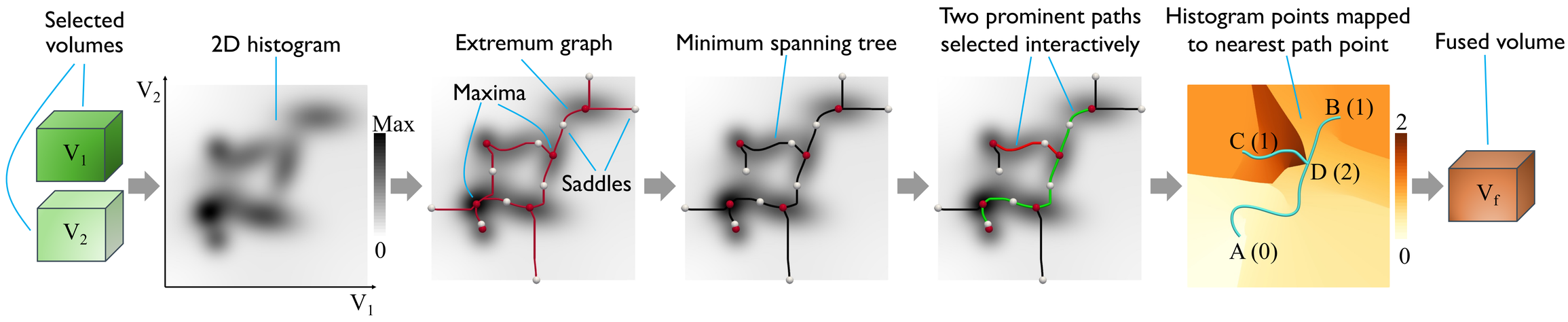
Contributions

A novel extremum graph-based technique to compute a fused volume from multivolume data.

Dimensionality reduction that retains important structure and topology-aware.

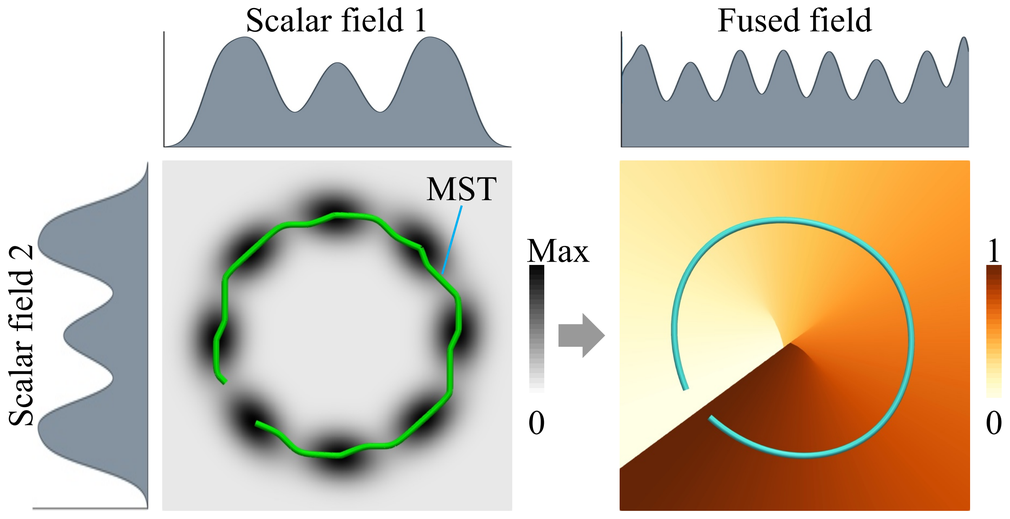
Enhanced rendering and segmentation using the fused volume.

Synthetic data walkthrough



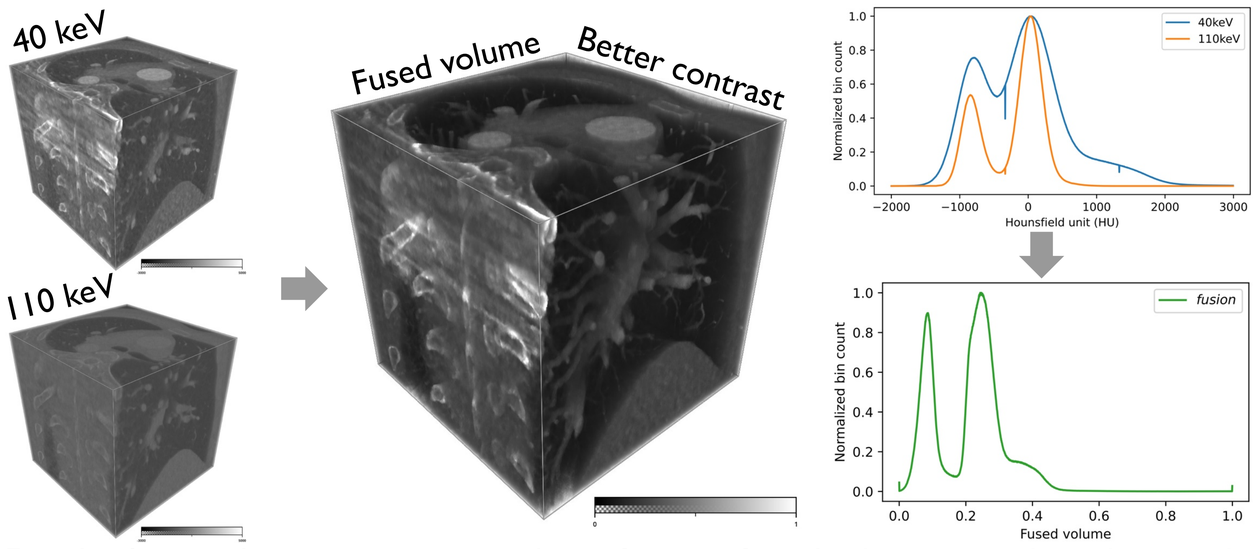
Fusion pipeline overview. Two least correlated volumes selected from multivolume dataset ⇨ 2D histogram ⇨ Extremum (maximum) graph [Forman 1998, Correa 2011] with maxima (red) and saddles (white) ⇨ Minimum Spanning tree (MST) ⇨ Two prominent paths interactively selected ⇨ Histogram points mapped to the nearest path, A-B ↦ [0, 1], C-D ↦ [1, 2] ⇨ Fused volume: Projected points mapped to the spatial domain

Dataset 1: Circular Gaussians



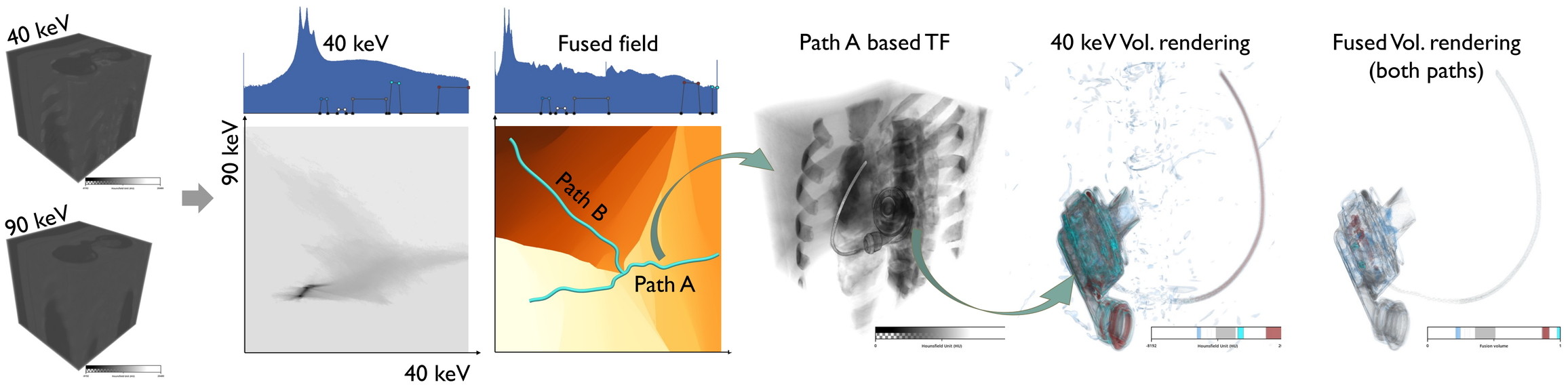
Fused field captures all 8 features. PCA will fail due to rotational symmetry and no clear principal axis.

Dataset 2: Human heart



Fused volume enhances contrast, combines features from both inputs, and emphasizes the right slope of the second peak (800–2000 HU) at 40 keV in the 1D histogram.

Dataset 3: Phantom lamb heart



Fused field histogram captures more features than the 40 keV volume. Path A based TF highlights multiple structures, including the phantom metallic heart. Volume rendering with a slightly adjusted TF for the fused volume, derived from both paths, reduces noise present in the 40 keV rendering.

Future work

Extend to multiple dimensions to handle multiple volumes.

Automatic path extraction.

Topology-aware spline mapping.

Interpreting the fused volume field in medical context.

Acknowledgements

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- **[Forman 1998]** R. Forman, "Morse theory for cell complexes," *Advances in Mathematics*, vol. 134, no. 1, 1998, 90–145.
- **[Flohr 2023]** T. Flohr, B. Schmidt, S. Ulzheimer, and H. Alkadhi, "Cardiac imaging with photon counting CT," *British Journal of Radiology*, vol. 96, no. 1152, 2023, article 20230407.
- **[Correa 2011]** C. Correa, P. Lindstrom, and P.-T. Bremer, "Topological spines: A structure-preserving visual representation of scalar fields," *IEEE Transactions on Visualization and Computer Graphics*, vol. 17, no. 12, 2011, 1842–1851.