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

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**Abstract**

*Photon-Counting Computed Tomography (PCCT) captures multiple volumetric datasets at different X-ray energy levels, offering rich spectral information for improved tissue differentiation and material analysis. However, the high dimensionality and redundancy of these datasets pose challenges for visualization using conventional CT workflows. Standard techniques, including single-channel transfer functions or dimensionality reduction methods, often fail to exploit the complementary nature of spectral data, missing important features. We propose a topology-guided volume fusion pipeline that reduces multi-volume spectral CT data into a single fused scalar field while preserving key anatomical and material structures. Using topological data analysis (TDA), specifically extremum graphs from 2D histograms of the two least correlated volumes, we identify prominent structures and map them onto a single scalar field, enabling effective visualization and segmentation with standard tools.*

**CCS Concepts**

• ***Human-centered computing*** → ***Scientific visualization;***

## 1. Introduction

Photon-Counting Computed Tomography (PCCT) captures per-photon spectral information, producing a set of volumes at different energy levels [FSUA23]. These volumes encode overlapping and complementary attenuation properties of materials, enabling better tissue differentiation and material characterization [GVR*25]. However, due to strong correlations between adjacent energy levels, standard visual exploration techniques (e.g., isosurfaces or 1D histograms) often fail to reveal the full spectrum of features present in the data.

This motivates the need to generate a fused volume that retains the key features of the multivolume dataset while remaining compatible with conventional visualization methods. We address this through a topology-guided pipeline, structured as follows: (1) we select the two least correlated volumes to maximize complementary information; (2) compute a 2D joint histogram from these volumes, capturing their joint density distribution; (3) interpret this histogram as a scalar field and compute its Morse–Smale (MS) complex [For98, YMS*21] to extract critical points—minima, maxima, and saddles—and their spatial relationships; (4) focus on maxima-saddle connections, forming the extremum (maximum) graph [CLB11], which better captures salient features such as tissue boundaries; (5) construct a minimum spanning tree (MST) over this graph, with edge weights defined by the absolute scalar difference between connected maxima and saddles; (6) extract a representative path along the MST, either automatically or interactively, capturing the main ridges of the histogram; (7) project all histogram points onto a smoothed spline fitted to this path and assign each a new scalar value based on its arc-length position; and finally, (8) transfer these scalar values back to the spatial domain to generate the fused volume. This fused field preserves joint features from both input volumes and significantly simplifies the visualization. An overview of these steps is provided in Figure 1, using a synthetic dataset for illustration.

## 2. Results

We evaluate our method on three datasets:

- **Circular Gaussians:** Figure 1 Demonstrates the method's ability to resolve eight overlapping bivariate features that are indistinguishable in individual 1D projections. PCA can't distinguish these featuers due to rotational symmetry and absence of a prominent direction, while our fused volume reveals all eight peaks clearly.
- **Human heart:** Figure 2 demonstrates the effectiveness of the method on a human heart dataset. Volumes at 40 keV and 110 keV are fused, and the resulting histogram (Figure 2(e)) captures combined features from both inputs. The fused volume exhibits enhanced contrast compared to either input alone.
- **Phantom lamb heart:** Figure 3 illustrates a complex case involving metal artifacts in the lamb heart, which produce signifi-

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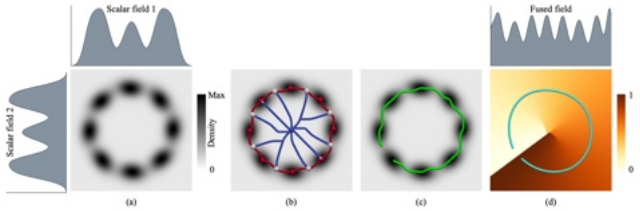
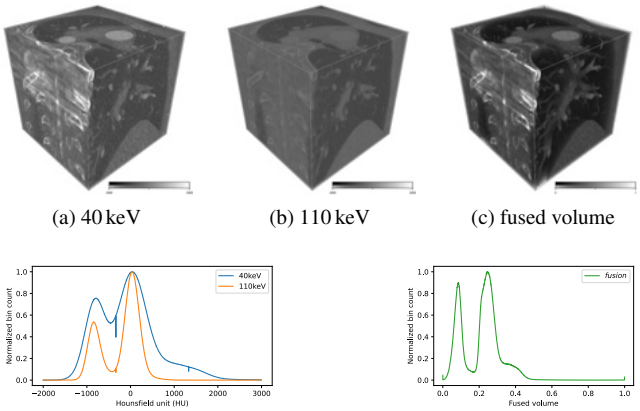



Figure 1: Volume fusion of two hypothetical volumes producing a 2D histogram resulting in eight Gaussian-distributed peaks on a circular path. (a) Synthetic 2D histogram; x-axis: scalar field from volume 1, y-axis: from volume 2; projected 1D histograms of individual volumes shown along the axes are unable to separate all features. (b) Morse–Smale complex of histogram density field; red: maxima, white: saddles, blue: minima. (c) Minimum spanning tree (green) of extremum graph, i.e., restricted to maxima and saddles; the longest simple path of the minimum spanning tree captures major ridge structure, traversing all eight Gaussian peaks. (d) Smooth spline (aqua) fitted to the path extracted in (c); fused scalar field generated by projecting histogram points to this spline; 1D histogram reveals the eight key features.




(a) 40 keV (b) 110 keV (c) fused volume

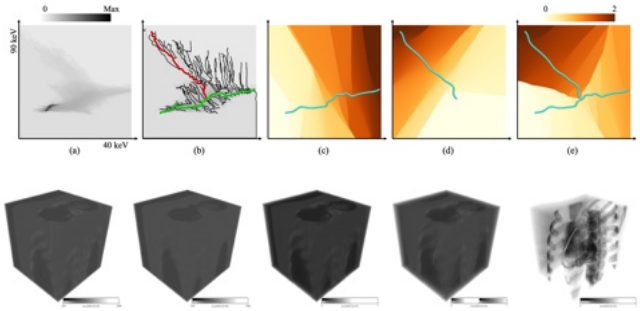
(d) (e)

Figure 2: Volume rendering of the human heart dataset. (a)-(c) A basic grayscale transfer function is applied to the input volumes for 40 keV and 110 keV, and the fused volume. (d)-(e) The 1D histograms corresponding to the underlying scalar fields.

cant noise and scatter in the joint histogram. Two distinct topological ridges (highlighted in red and green) are extracted, fused separately, and then combined to emphasize different anatomical materials. Figure 4 presents the designed transfer functions and corresponding renderings for the 40 keV input and the fused volumes. The red path captures the noisy scatter visible in Figure 3(b), while the fused volume generated using both paths significantly reduces this noise, as seen in Figure 4(c,d).

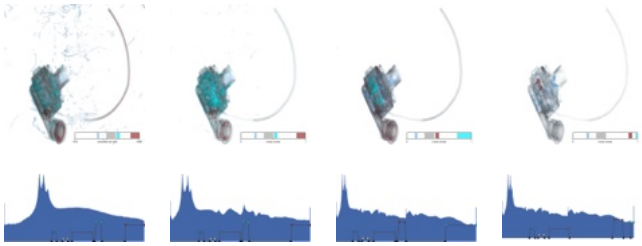
## 3. Conclusion

We present a topology-guided method to fuse multi-energy spectral CT volumes into a single scalar field that preserves key anatomical features while reducing dimensionality, allowing use with standard CT tools. Using extremum graphs and spline projections in histogram space, our approach enables effective visualization and segmentation with feature-aware simplification and compatibility with traditional rendering. Future work will extend to multiple volumes, automate path extraction, and incorporate more topological information.




(f) 40 keV (g) 90 keV (h) fused volume (c) (i) fused volume (e) (j)

Figure 3: Phantom lamb heart dataset. Volume fusion (a)-(e) and volume rendering (f)-(j). (a) Log scale histogram exhibiting undesired scatter caused by the presence of an artificial metallic heart. (b) Two prominent paths, shown in red and green, are interactively selected to extract branching structures within the histogram. Three fused volumes are generated: (c) grid parameterization along the green path (used in (h)), (d) along the red path, and (e) the combined parameterization merging both paths (used in (i)). (j) slightly adjusted transfer function for fused volume (c).



(a) 40 keV (b) fused volume (green path) (c) fused volume (both paths) (d) fused volume (both paths)

Figure 4: Volume rendering of the artificial heart in the phantom lamb heart dataset. (a)-(b) The fused volume results in less clutter with an almost identical transfer function. (c)-(d) The 1D histogram of the fused volume reveals more features and thereby eases the transfer function design.

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