Research Direction: Neural Scene Representations for Interactive Exploration of Complex Volumetric Data
Project Title: AI for Volumetric Exploration in Reality (AIVER): Neural and Gaussian Scene Representations for Volumetric Analysis

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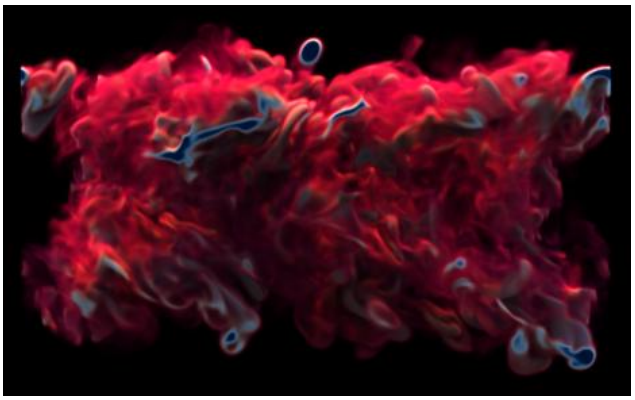

Figure 1. *Preliminary volumetric rendering study developed at UC Davis' VIDi Labs using Open Volume Renderer (OVR). A turbulent scalar field is visualized with a custom transfer-function and gradient-aware shading pipeline, demonstrating preservation of fine-scale volumetric structure and visual fidelity under dense field conditions. This example motivates the need for compact, representation-driven approaches that support real-time, immersive exploration of complex unstructured data.*

1. Research Summary

Unstructured volumetric datasets are central to computational science and engineering, yet their irregular geometry and scale make real-time visualization difficult, especially in immersive environments. Conventional desktop tools support unstructured-grid visualization but remain constrained by a limited field of view, restricted spatial context, and high rendering cost. AIVER introduces a neural scene representation and AI-accelerated rendering framework enabling real-time VR/XR exploration of 3D unstructured volumes. By combining Gaussian Splatting–based encoding, view-consistent neural reconstruction, and GPU-optimized rendering, the system produces compact volumetric representations that support interactive exploration and expressive visual mapping (Figure 1). AIVER establishes the computational foundation for scalable immersive analysis of multivariate scientific data. More broadly, AIVER treats immersive environments as a testbed for studying how neural scene representations can enable scalable, interactive exploration and control of complex high-dimensional data.

2. Motivation

Unstructured grids arise naturally in simulations involving complex geometry, multi-scale physics, and adaptive spatial refinement, including applications in fluid dynamics, cardiac flow, and structural mechanics. However, their irregular connectivity and scale pose fundamental challenges for interactive visualization. Irregular topology complicates efficient GPU traversal, while interpolation requires repeated neighborhood queries that are computationally expensive. As data sizes grow, maintaining interactive frame rates becomes increasingly difficult, particularly when supporting multivariate fields and expressive visual mappings. Existing interactive visualization systems lack compact representations that jointly support rendering quality, computational efficiency, and flexible interaction, limiting their effectiveness in real-time and immersive settings. Scientists increasingly rely on volumetric data to validate models, diagnose errors, and explore emergent phenomena, but without immersive, real-time visualization, critical structure and multivariate relationships remain inaccessible.

3. Core Technical Advances

AIVER contributes a unified computational approach for immersive unstructured-volume visualization:

- A Gaussian Splatting-based neural representation for unstructured volumetric data, enabling compact, view-consistent encoding

- A representation layer supporting multivariate and multidimensional attributes, decoupled from specific visual mappings
- An AI-accelerated real-time rendering pipeline leveraging neural interpolation and GPU optimization
- Interactive immersive exploration tools for examining structure, flow, and spatial relationships

These contributions establish a scalable foundation for long-term research on neural representations for scientific data.

4. Methodological Approach

AIVER's pipeline integrates neural representation learning with high-performance rendering:

- **Neural volumetric encoding:** unstructured volumes are transformed into splat-based neural primitives parameterized by position, covariance, density, and attribute channels.
- **Gaussian Splatting reconstruction:** splats accumulate along view rays, providing real-time, differentiable, and view-consistent reconstruction.
- **AI-accelerated rendering:** neural interpolation, spatial hashing, and level-of-detail selection reduce rendering cost while preserving fidelity.
- **Expressive visual mapping:** attribute channels feed into flexible transfer functions supporting multivariate visualization in VR/XR.
- **Interactive immersion:** VR headset integration enables exploration of spatial scale, structure, and multivariate relationships not visible in desktop environments.

5. Significance

- Enables immersive, real-time visualization of unstructured grids previously too large or complex for interactive rendering.
- Introduces a neural representation strategy that generalizes across scientific domains.
- Provides a compact encoding that supports multivariate analysis and rich visual mapping.
- Establishes AI-accelerated rendering as a foundation for next-generation immersive exploration.
- Empowers scientists to directly visualize large-scale simulations in VR/XR environments
- Demonstrates how neural scene representations can bridge generative modeling, high-performance systems, and interactive analysis for complex data domains.

This research direction positions neural scene representations as a unifying abstraction for interactive analysis across generative modeling, scientific computing, and immersive systems.

6. Future Extensions

- Multivariate and multi-field representation learning.
- Incorporation of temporal dynamics for 4D time-varying data.
- Adaptive neural representations for multi-resolution volume exploration.
- Integration of physics-guided priors to enhance interpretability.
- Real-time interaction techniques for collaborative XR scientific analysis.

7. Role and Leadership

Michael Martin led the AIVER project, formulating the research objectives, designing the methodological framework, and authoring the complete technical proposal. He defined the neural and Gaussian representation strategy, developed the AI rendering approach, and structured the system architecture for immersive volumetric analysis. Martin conducted all conceptual design, algorithmic planning, and preliminary studies. A condensed one-page summary derived from this work was submitted to Argonne National Lab by Dr. Kwan-Liu Ma. Dr. Ma provided research advisement throughout the project.

Reference

Martin, M. R., *AI for Volumetric Exploration in Reality (AIVER) – Neural Scene Representations and AI-Accelerated Real-Time VR/XR Visualization of Unstructured Volumetric Data,* Research Proposal, November 2025.
https://doi.org/10.13140/RG.2.2.27634.36807