Holographic Visualization and Quantitative Analysis of Brain Imaging Data

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Abstract. Medical imaging data is inherently complex and often difficult to interpret using traditional 2D visualization methods. This project addresses this challenge by combining quantitative analysis with advanced 3D holographic visualization to enhance the interpretability of brain imaging datasets. Using VTK for data processing and Looking Glass for visualization, we segmented brain data into four distinct regions, performed volumetric and surface area calculations, and extracted spatial properties such as centroids and principal axes. These insights were visualized on the Looking Glass holographic display, providing an interactive and immersive experience. The workflow aims to bridge the gap between traditional analytics and innovative visualization, demonstrating the potential of holographic displays in medical imaging interpretation. Future work includes automating the integration pipeline and exploring applications for other medical datasets.

Links:

- **GitHub Repository:** `https://github.com/Sandhya-VA/CS6357FinalProject/`
- **Holographic Display Demo:** `https://youtu.be/X9WPEu3k1sg`

1 Methods

1.1 Quantitative Analytics

The analytics component involved processing and analyzing brain imaging data to derive meaningful insights. Using the Visualization Toolkit (VTK), the following steps were implemented:

- **Data Segmentation**: Brain imaging data was provided as `.vtp` files, representing the left and right hemispheres. We segmented the data into four regions—Left-Front, Left-Back, Right-Front, and Right-Back—based on the spatial coordinates (`x`, `y`, `z`) of each point. The segmentation logic was written in Python using conditional rules to assign regions and colors.

- **Color Coding**: Distinct RGB color codes were assigned to each region using `vtkUnsignedCharArray`. These codes ensured clear differentiation of regions during visualization.
- **Region Combination**: The segmented data from the left and right hemispheres was merged using `vtkAppendPolyData`, preserving the color-coded regions in a single dataset.
- **Point and Cell Counts**: The spatial density of each region was evaluated by counting the number of points (`polydata.GetNumberOfPoints()`) and cells (`polydata.GetNumberOfCells()`).
- **Volume Estimation**: Using the `vtkMassProperties` module, we calculated the volume of each region after applying surface triangulation. This process ensured accurate measurements.
- **Surface Area Estimation**: Surface areas were calculated using Delaunay triangulation and subsequent mass property evaluation.
- **Principal Axes and Centroids**: The principal axes of each region were determined through eigenvalue and eigenvector computations using VTK's matrix algebra tools. The centroid, representing the geometric center, was computed as the mean of all spatial coordinates within each region.
- **Validation and Statistics**: To verify the correctness of segmentation and ensure the integrity of the combined dataset, we extracted unique colors and validated the point distributions across all regions.

1.2 Holographic Visualization

The holographic visualization of the brain imaging data was achieved using the Looking Glass Portrait device, a state-of-the-art holographic display. The workflow involved data preparation, hardware setup, software configuration, and rendering. The steps are as follows:

Data Preparation for Holographic Rendering

- Processed brain data was exported as `.ply` and `.stl` files using VTK's `vtkPLYWriter`.
- The exported files contained both color-coded segmentation information and isolines, enabling enhanced clarity during holographic rendering.

Hardware Setup for Looking Glass Portrait

- **Device Connection**: The Looking Glass Portrait was connected to a Windows PC using the USB-C cable for power and data transfer, and an HDMI cable for video output.
- **Display Configuration**:
  - Navigate to Windows `Display Settings`.
  - Set the Looking Glass Portrait as an external display with a resolution of `1536 x 2048`.
  - Adjust the display orientation to `Portrait` and set the Portrait display as an `Extended Display`.

Software Configuration

- **Looking Glass Bridge**: Installed and configured the Looking Glass Bridge software to establish seamless communication between the holographic display and the Windows PC.
  - Downloaded the Looking Glass Bridge installer from the Looking Glass Factory documentation.
  - Launched the software and ensured that the device was detected as an external display.
  - Enabled automatic display calibration to ensure correct depth and alignment.

Model Loading and Rendering

- The processed `.ply` files were imported into the Looking Glass Model Viewer. This tool natively supports holographic rendering and allowed us to:
  - Rotate, zoom, and pan the 3D brain models.
  - Examine spatial relationships between regions interactively.

2 Results and Interpretation

2.1 Analytics

Surface Area Estimation: To assess boundary sizes and structural differences, we calculated the surface areas of the segmented brain regions using Delaunay triangulation:

- **Right-Back (255, 255, 0)**: 31,999.25 mm^2
- **Left-Back (0, 255, 0)**: 33,310.53 mm^2
- **Left-Front (255, 0, 0)**: 25,956.74 mm^2
- **Right-Front (0, 0, 255)**: 26,221.87 mm^2

Interpretation: Back regions (Left-Back and Right-Back) exhibit larger surface areas, reflecting greater cortical folding.

Point and Cell Counts To understand spatial density, we analyzed points (vertices) and cells (connectivity units) in each region:

- **Right-Back (255, 255, 0)**: 87,385 points, 563,236 cells
- **Left-Back (0, 255, 0)**: 91,423 points, 563,236 cells
- **Left-Front (255, 0, 0)**: 50,373 points, 563,236 cells
- **Right-Front (0, 0, 255)**: 52,441 points, 563,236 cells

Interpretation: Higher point density in back regions indicates more intricate structures compared to the front regions.

Volume Calculations To measure the spatial size of each region, volumes were computed:

– **Right-Back (255, 255, 0)**: 44,099.57 mm^3
– **Left-Back (0, 255, 0)**: 390,178.08 mm^3
– **Left-Front (255, 0, 0)**: 10,650.21 mm^3
– **Right-Front (0, 0, 255)**: 17,423.16 mm^3

Interpretation: The Left-Back region has the largest volume, while the Left-Front is the smallest, highlighting structural size differences.

Point Counts by Hemisphere Point distributions across hemispheres were analyzed to verify segmentation accuracy:

– **Left Hemisphere:**
  - Left-Front: 50,373 points
  - Left-Back: 91,423 points
– **Right Hemisphere:**
  - Right-Front: 52,441 points
  - Right-Back: 87,385 points

Interpretation: Points are correctly segregated into their hemispheres, with posterior regions (Left-Back and Right-Back) showing higher density.

Principal Axes and Centroids Principal axes and centroids were computed to analyze orientation and positioning:

– **Right-Back (255, 255, 0):** Eigenvalues: [247.58, 634.07, 743.67], Centroid: [53.03, -42.21, 13.94]
– **Left-Back (0, 255, 0):** Eigenvalues: [260.45, 634.88, 791.77], Centroid: [-7.28, -43.22, 13.33]
– **Left-Front (255, 0, 0):** Eigenvalues: [229.15, 455.90, 656.23], Centroid: [-4.94, 30.12, 13.42]
– **Right-Front (0, 0, 255):** Eigenvalues: [224.99, 481.56, 650.96], Centroid: [51.22, 30.78, 12.32]

Interpretation: Eigenvalues highlight dominant axes, with the Right-Back region showing the greatest elongation. Centroids confirm correct spatial alignment.

2.2 Visualization

Generating the 3D Brain Model: To create a cohesive and interpretable 3D brain model, the following steps were performed:

Step 1: Combining Hemispheres We started by merging separate .vtp files representing the left and right hemispheres of the brain. The result is depicted in the leftmost image, showing the merged, uncolored brain structure.

Step 2: Color-Coding Hemispheres The next step involved segmenting the unified model into two regions corresponding to the left and right hemispheres. Each hemisphere was assigned a distinct color for clarity: red for the left hemisphere and blue for the right hemisphere. This segmentation allows for a clear visualization of the hemispheric division, as shown in the middle image.

Step 3: Quadrant-Based Segmentation Finally, the brain was divided into four quadrants: Left-Front (red), Left-Back (green), Right-Front (blue), and Right-Back (yellow). This segmentation was achieved using predefined criteria for spatial orientation. The quadrant-based segmentation facilitates region-specific analysis, as displayed in the rightmost image.

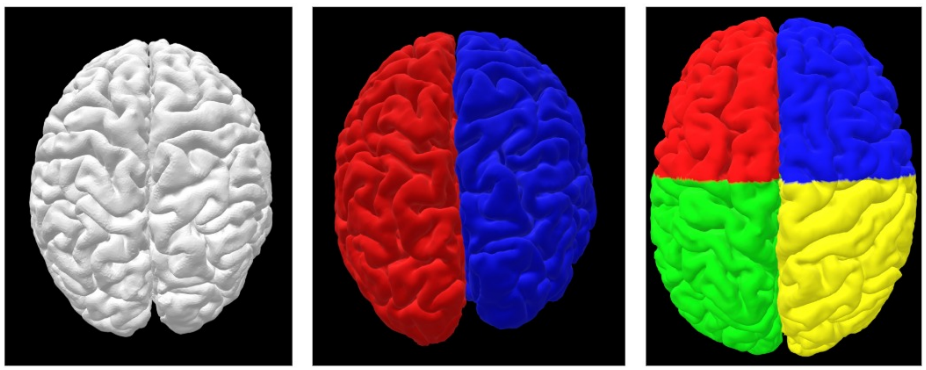

Fig. 1. (Left) Merged brain model, (Middle) Color-coded segmentation into left (red) and right (blue) hemispheres, (Right) Quadrant-based segmentation of the brain into Left-Front, Left-Back, Right-Front, and Right-Back regions.

Interpretation: The series of images illustrates the progression from an unsegmented 3D brain model to a fully segmented representation, with distinct hemispheric and quadrant divisions. This stepwise visualization provides a structured foundation for quantitative analysis, enabling region-specific insights into the brain's spatial properties and structural composition.

2.3 Visualization Results — VTK Rendering

Description: We showcase three distinct visualization perspectives using VTK rendering tools:

- **Left Image:** Brain regions labeled with volumes allowing clear spatial correlation of volumetric data with anatomical structures.
- **Center Image:** Cross-sectional slices along the Y-axis, providing an intuitive understanding of internal structures.
- **Right Image:** Slices overlaid with isolines to enhance boundary clarity and structural delineation.

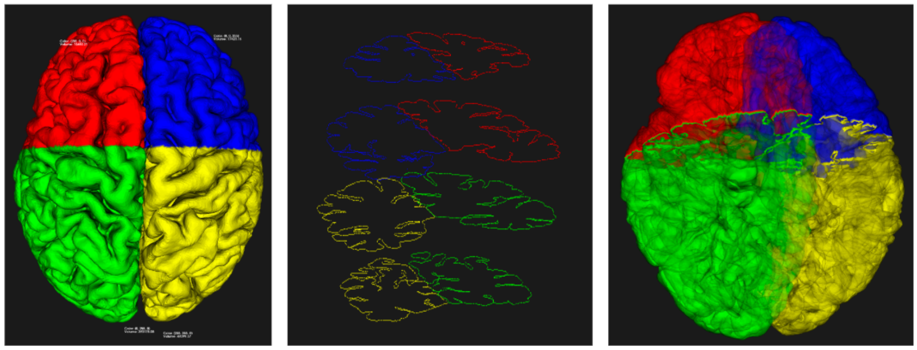

Fig. 2. Three views of the segmented brain visualized using VTK tools.

Interpretation: These visualizations provide both macroscopic and sectional insights into brain anatomy, effectively combining quantitative metrics and spatial geometry. The isolines in the right image further highlight regional boundaries, assisting in distinguishing functional and structural domains.

3 Discussion

3.1 Satisfaction with the Results

Overall, we are satisfied with the outcomes of this project. The Looking Glass Portrait allowed us to achieve an immersive and interactive visualization of complex brain imaging data, which successfully highlighted regional segmentation. The quantitative analytics provided detailed insights into the structural properties of each brain region, such as volume, surface area, and principal axes. These results demonstrated the feasibility of combining advanced visualization techniques with quantitative analysis, fulfilling the core objectives of our study. However, some limitations remain. The reliance on external tools such as the Looking Glass Model Viewer limited the flexibility of our workflow. Despite this, the results provided a clear proof of concept for holographic medical imaging.

3.2 Opportunities for Improvement

If we were to revisit this project, several areas could be improved:

- **Direct Integration with Looking Glass**: One significant limitation was the inability to programmatically render 3D models directly onto the Looking Glass device. Developing a direct integration pipeline would streamline the workflow and enhance flexibility.
- **Automation of Rendering Workflow**: The current process of exporting and loading files into the Model Viewer could be automated to save time and reduce manual intervention.

- **Dynamic Visualization**: Adding real-time interaction features, such as adjustable segmentation thresholds or live annotation, would make the visualization more versatile.

3.3 Lessons Learned

This project provided valuable insights, both technically and conceptually:

- **Interdisciplinary Integration**: We learned the importance of combining analytical rigor with user-friendly interfaces.
- **Flexibility in Problem Solving**: The need to pivot from direct rendering to file-based rendering taught us the importance of adapting to technical constraints while maintaining project goals.
- **Collaboration with Emerging Technologies**: Working with the Looking Glass Portrait underscored the potential of holographic displays in medical imaging, as well as the challenges of integrating cutting-edge hardware into standard workflows.
- **Attention to Detail**: Managing color-coded segmentation and file compatibility highlighted the importance of precision in data preparation and visualization.

3.4 Future Work

Building on this project, several directions for future research and development are apparent:

- **Direct Programmatic Rendering**: Developing libraries or APIs to directly render VTK objects on the Looking Glass Portrait would greatly enhance efficiency and scalability.
- **Broader Dataset Applications**: Expanding the analysis to other medical imaging datasets, such as CT or MRI scans from different anatomical regions, could demonstrate the versatility of this workflow.
- **Machine Learning Integration**: Incorporating machine learning models to analyze segmentation boundaries or predict anomalies could add an intelligent layer to the visualization process.
- **Contribution to Open-Source Tools**: Developing open-source libraries to directly interface with Looking Glass devices would democratize access to holographic visualization technology. Additionally, creating plugins or API bindings to integrate Looking Glass displays with tools such as 3D Slicer would enable seamless integration into existing medical imaging workflows.

4 Conclusion

This project demonstrated the potential of combining quantitative analytics with holographic visualization to enhance the interpretation of medical imaging data. By leveraging the Looking Glass Portrait device, we successfully created an

immersive and interactive 3D visualization of brain imaging data, highlighting regional segmentation. The integration of advanced analytics provided detailed insights into structural properties such as volume, surface area, and principal axes, which were essential for understanding brain regions.
Despite challenges related to direct rendering, our workflow achieved its objectives through adaptations that emphasized flexibility and problem-solving. The project highlights the feasibility of holographic displays in bridging the gap between complex data and intuitive exploration, laying a foundation for future advancements in medical imaging and visualization technologies.

5 Acknowledgments

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6 References

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