Poster: BrainTrek – An Immersive Environment for Investigating Neuronal Tissue

Michael Morehead† Quinn Jones† Jared Blatt† Paul Holcomb‡ Juergen Schultz♮ Tom DeFanti♮
Mark Ellisman♯ Gianfranco Doretto† George A. Spirou‡
†CSEE Dept., West Virginia University, ‡ Center for Neuroscience, West Virginia University School of Medicine
♮ Qualcomm Institute, UC San Diego, ♯ National Center for Microscopy and Imaging Research, UC San Diego

Abstract

The high degree of complexity in cellular and circuit structure of the brain poses challenges for understanding tissue organization, extrapolated from large serial sections electron microscopy (ssEM) image data. We advocate the use of 3D immersive virtual reality (IVR) to facilitate the human analysis of such data. We have developed and evaluated the BrainTrek system – a CAVE-based IVR environment with a dedicated and intuitive user interface tailored to the investigation of neural tissue by scientists and educators.

Index Terms: I.3.7 [COMPUTER GRAPHICS]: Three-Dimensional Graphics and Realism—Virtual reality; H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Input devices and strategies; J.3 [Computer Applications]: LIFE AND MEDICAL SCIENCES—Biology and genetics;

1 Introduction

Technical advances over the past decade have increased the speed of acquiring ssEM images for constructing neural wiring diagrams, or connectomes. Several groups have realized the value of these image volumes beyond assembling wiring diagrams and thus investigate the 3D structure of brain cells and their spatial relationships. From this approach we hope to appreciate not only functional contacts between neurons, but also among neurons and glia, and gain insight into higher order organizational features of brain tissue. These high-resolution data sets offer opportunities to study novel aspects of 3D brain structure, for which analysis tools are in early stages of development. We suggest that 3D visualization of complex brain structure is a useful first step to gain initial insight into general features of organization that can be rephrased as hypotheses for testing by subsequent quantitative analysis.

In this work we develop and evaluate BrainTrek (see Figure 1), a 3D IVR environment to address the challenges expressed above, and which complements existing approaches, such as [1], that have a stronger focus on connectomics, and do not utilize IVR. In particular, the contributions of this work can be summarized as follows:

- A 3D IVR system for displaying high-resolution 3D cell models extracted from ssEM image volumes of neuronal tissue at nanoscale resolution
- A 3D user interface (UI), with preliminary evaluation by users, for interaction with and manipulation of spatially calibrated neuronal models
- An enhanced access and control of system features through a combined use of a wireless tablet and a wand
- A management system for accessing and browsing collections of 3D neuron models through developmental ages and space
- A pre-processing pipeline to balance performance and visualization accuracy

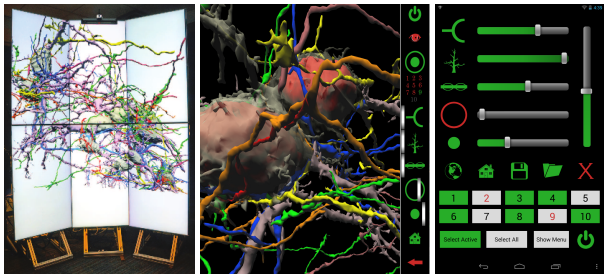


Figure 1: **BrainTrek.** *Left:* A full view of the six 55-inch panel screens displaying nine complete cell models. The tracking system rests above the top middle panel. *Center:* A close-up view of the BrainTrek system and on-screen menu that allows for modification of the cell scene. Two cells with different cell body transparencies reveal the contained nucleus (red) with varying clarity. *Right:* Tablet layout designed for the Nexus 7, which allows for modification of the scene with sliders and buttons.

2 3D IVR System

Our CAVE system is comprised of six 55-inch 3D enabled LCD/LED screens (LG 55LM9600) and follows the TourCAVE design developed and tested at Calit2 [5]. We employ an ART (Advanced Realtime Tracking) SmartTrack system for head and wand tracking. The computer driving the CAVE contains an Intel Core i7-3820 processor, two GeForce GTX 680 GPU cards, and 32GB of RAM. The machine is running CentOS 6.3. A Nexus 7 tablet provides an alternative user interface.

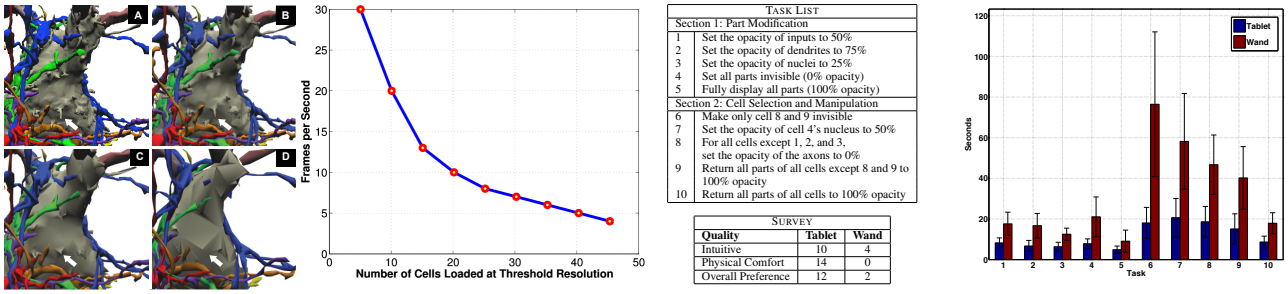
CalVR provides the middleware framework that drives BrainTrek. Developed for CentOS, CalVR is a C++ object-oriented class hierarchy that utilizes the OpenSceneGraph library and OpenGL to render graphic output. It supports multiple 3D menu systems, navigation methods, and tracking and display systems [4]. BrainTrek builds upon and significantly enhances the core of CalVR.

3 Graphics Interface

Inspired by Google Body Browser, each cell part (soma, nucleus, dendrite, input, axon) was assigned a dedicated icon. An icon based menu was developed to facilitate ease of recognition and approachability for novice users. Every cell part has a dedicated slider to control its transparency. A main slider can be used to bring a cell into the picture one part at a time, creating the feeling of moving through layers. Currently, the expandable interface has been used for the independent control of up to 10 cells, which permits exploring local geometric relationships without overwhelming the view.

4 Wand and Tablet

The wand is used for navigation or manipulation of the menu options. Transparency sliders are moved by selecting and dragging within the menu. A cell selection headsup display indicates which cells are currently alterable. Fine manipulation of the interface with the wand was unwieldy due to limited tracking resolution. An alternative interface was developed using an Android tablet with a custom WIMP interface. Note that the tablet is not used for navigation, only system control as described in [3]. The touch screen



TASK LIST

Section 1: Part Modification	
1	Set the opacity of inputs to 50%
2	Set the opacity of dendrites to 75%
3	Set the opacity of nuclei to 25%
4	Set all parts invisible (0% opacity)
5	Fully display all parts (100% opacity)
Section 2: Cell Selection and Manipulation	
6	Make only cell 8 and 9 invisible
7	Set the opacity of cell 4's nucleus to 50%
8	For all cells except 1, 2, and 3, set the opacity of the axons to 0%
9	Return all parts of all cells except 8 and 9 to 100% opacity
10	Return all parts of all cells to 100% opacity

SURVEY

Quality	Tablet	Wand
Intuitive	10	4
Physical Comfort	14	0
Overall Preference	12	2

Figure 2: **Evaluation.** *Feature Visibility (Far Left, A-D):* Specific neuronal parts and features were choosen to provide a metric for effects of varying resolution. Below 2 vertices/μm^2, even large objects like the cell body have distorted features. Above 8 vertices/μm^2, all features are sufficiently preserved. *System Performance (Middle Left):* Rendering frequency update in frames per second (fps) versus the size of the cell set in the scene. Each cell model is set to the minimum resolution in vertices/μm^2 that guarantees that all the features are visible. *Task list and comparative survey (Middle Right):* Each participant was educated on a specific device and asked to perform the tasks in the top table. Once participants had tried both input devices, they selected which device they preferred for various qualities. *Tablet vs Wand (Far Left):* User interaction times are measured for specific tasks for both the wand and tablet. The first five tasks only involve global changes to the set of cells, while the latter five involve specific cell selection and modification.

capabilities of the tablet translated well into implementation of sliders from our UI.

5 Cell Sets Management

We created the Mission Control user interface tool to select 3D model files from our archive for display using CalVR. Mission Control is a light-weight custom application for the indexing, selection, and loading of cellular model structures. Individual cells are organized by animal age, and indexed by assigned number. Once a set of cells from a particular age are selected, an automated Python script rewrites the configuration XML file. This set may be viewed immediately, or saved for later viewing. Beyond scene manipulation, efforts were made to increase the collaborative capability of CalVR. A view saving system was implemented to store combinations of camera position and cell presentation deemed useful for insights into nervous system structure. Either single frames or movies of camera and scene manipulation can be saved. This system can be easily expanded for more attributes, so the inclusion of annotations or voice lectures could be added, making BrainTrek a useful teaching tool.

6 Neural Data Optimization

Since finite rendering power limits visualization of large volumes, a balance point between model accuracy and GPU-load was determined. We identified a list of small neuronal features and rate their visibility at various model resolution (Figure 2A-D). Different resolutions were obtained with a quadratic edge mesh decimation approach [2]. Full resolution models had 64 vertices/μm^2. At 8.2 vertices/μm^2, fine processes called neurites (white arrow) remain visible, but below 5 vertices/μm^2, fine macro processes are incorrectly shortened due to mesh decimation approximations. At resolution lower than 2.3 vertices/μm^2, neurons appear blocky and distorted (Figure 2D).

The left plot of Figure 2 shows the relationship between the size of the cell set rendered in the scene, and the frame rate. The cell resolution was set at the minimum that guarantees the visibility of each feature, i.e. 8.2 vertices/μm^2. The system responsiveness starts suffering at frame rates below 15 fps. Since at full resolution the number of vertices per neuron averaged at 264,207 $\pm$ 51,267, without decimation the display of only five cells lowered the frame rate to 12fps, and reached 5fps for 9 cells, yielding a particularly sluggish viewing experience, and suggesting the need for developing neuronal model-based decimation algorithms in the future.

7 UI Evaluation

We performed an initial study on the comparative advantages of our wand interaction system and the tablet interface. 14 participants were recruited. Each was randomly assigned to either Group A or Group B. The groups only dictate which input device the participant tested first. Participants were introduced to their first input device via a five minute tutorial. Participants then performed a series of tasks manipulating a nine cell data set projected in 3D (see the task list in Figure 2). Task completion and time measurements revealed significant advantage of the tablet (all except tasks 2 and 5 reached $p < 0.05$, Wilcoxon Signed-Rank Test; right plot of Figure 2). The input device was switched to the alternative and the process repeated. Finally, the participants were given a survey comparing the two. Most participants found the tablet to be more intuitive (see survey in Figure 2).

Our neuroscience group has used 3D visualization to identify a novel type of cell polarity and axonal extension along dendrites during neural circuit formation in early brain development. Observing these features using 3D IVR has informed design of offline quantification procedures.

8 Discussion and Future Work

We have evaluated system metrics to guide hardware design of a 3D IVR. We have designed a user interface to control the display of a selected number of cells that is intuitive and rapidly manipulated via a tablet. Qualitatively, the system has been useful to neuroscientists to explore local cellular interactions. Future plans include quantification of its utility and system enhancements such as tablet navigation, and increasing the flexibility of user interaction by implementing hand-tracking and voice activation.

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