Visual Exploration and Interaction with Scientific Data in Virtual Reality

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ABSTRACT

DEMO PAPER: As consumer-level virtual reality hardware becomes more readily available and affordable, new applications for it are being explored at an impressive rate. Virtual reality combined with gloves to track gestures and movements allows for considerably more immersive interactions and experiences.

In this demonstration, we explore one such application in using the latest virtual reality hardware to develop new immersive ways for users to explore and interact with scientific data. More specifically, using the example of neuroscience data, i.e., brain models, we demonstrate how users can analyze and understand data by interacting with it in virtual reality using gestures to analyse the three dimensional representations of the data.

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1 BACKGROUND

Real world examples of scientific models make for an extremely challenging data set to present through visualization. They are generally incredibly complex and large, making the task of visualizing them difficult. Due to their intricate 3D nature, full 2D representations are effectively infeasible.

For such datasets, the better solution is digital 3D models, as it allows for a much easier to interpret representation, as aspects like depth can be properly observed. The way we currently view these digital models, however, introduces more flaws, as they are typically only viewed on a flat screen of some form, effectively making the user peer through a small window at the model, viewing and interacting with it from what feels like a distance. At the same time, the perception of depth is completely lost.

A particularly difficult scientific dataset to visualize are neural networks. While multiple approaches to visualize neural networks have been developed, it is still difficult to truly understand the structure and connectivity of them. Connectivity matrices, for example, can perfectly describe how the neurons in a network are connected but do not provide any intuition about the actual layout or shape. Similarly, 2D visual diagrams become confusing and hard to understand, as the number of overlapping connections tends to be extremely high given the high degree of connectivity in neural networks. Most of the research carried out recently on visualizing neural networks developed novel means to visualize statistics of networks [4, 8]. While they are easy to understand, the resulting statistics of course still do not give a sense of the depth, structure, and connectivity of the network.

Virtual reality allows for a substantially better experience and a more natural way to interact and explore data. By putting the user in virtual reality, many limitations of existing visualization techniques are removed. Visualizing scientific spatial data in VR has been shown to lead to more insight and discoveries [3]. It is already used to assist with data analysis in many scientific fields, such as paleontology [5], brain tumors [10] and MRI results [2]. As a large aspect of the model, we will be visualizing the spatial arrangement of the network; we feel that the study of a data structure like this will benefit greatly from the use of VR to do so, and will allow scientists to make more insightful observations.

Along with the headset advances, new hardware to accompany these headsets is being constantly developed and released, such as the Virtuix Omni, an omnidirectional treadmill designed to allow users to walk in virtual environments while wearing a VR headset [1]. Another example is the current development by various companies of data gloves, which track a user's hand/arm movements and gestures, allowing them to be used for interaction in virtual reality applications.

In this paper, we describe a demonstration where we use the example of a neural network to demonstrate a new approach to visualize, explore and interact with scientific data and models. Our proposed solution provides an interface for users to view and interact with a highly accurate and detailed 3D model of a neural network using virtual reality technology. In the following, we describe our approach, how we visualize the neural network and how users can interact with it using gestures. We illustrate the scenarios of the demonstration with screenshots as well as videos.

2 MIND EXPLORER VR

To support neuroscientists in analyzing and exploring detailed brain models, we develop Mind Explorer VR, a virtual reality application for the HTC Vive. Its goal is to allow scientists to inspect and interact with an extremely detailed model of a rat's neocortex [6, 7] in a fully immersive way. The scientist is surrounded by the model in virtual reality, and using Manus VR data gloves, is able to use their hands to manipulate the model, perform spatial queries on different parts of the neocortex to retrieve more detailed representations, and see how signals propagate throughout the network. It enables the visualization of a complex data structure at an unprecedented level of detail, and in an engaging manner.

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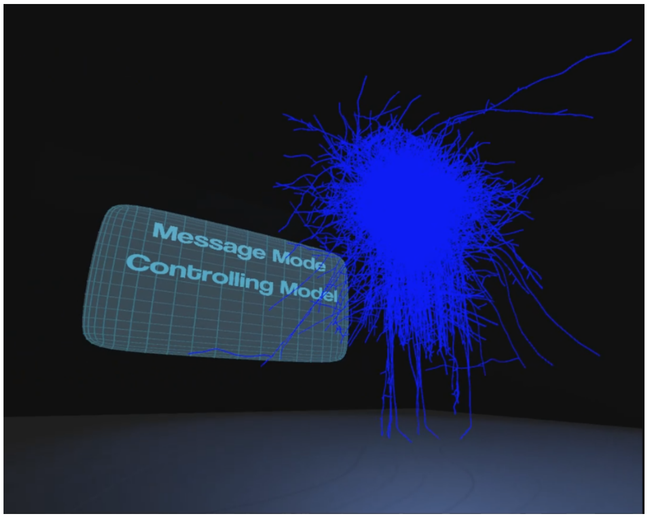

Figure 1: A small part of the rat's neocortex down-sampled model rendered in virtual reality. Each segment of a neuron branch is represented by a line.

The HTC Vive also allows for a room-scale VR experiences so that the user will be able to physically walk around the virtual environment and the model.

The data visualized is the most detailed model of a neural network to date, visualizing each neuron on an unprecedented level of detail. The data has been gathered and generated in the Blue Brain Project (BBP [6]), in which, to conduct simulation-based research in neuroscience, the neuroscientists build biophysically realistic models, with data acquired in anatomical research on the cortex of the rat brain. The project began by focusing on the elementary building block of the neocortex, a neocortical column of about 10,000 neurons. Morphologically speaking, each of these neurons has branches extending into large parts of the tissue in order to receive and send out information to other neurons.

The models currently investigated in the BBP and thus visualized in Mind Explorer VR contain up to 500,000 neurons, but it is foreseen to ultimately extend this by orders of magnitude to microcircuits of the size of the human brain (~10^{11} neurons). More importantly, the circuits will at the same time become much more fine-grained, modeling the neurons at a subcellular level with hundreds of thousands of structural elements per neuron. Mind Explorer VR primarily uses the mesh datasets of the neuron models representing the surface of the neurons as meshes (with billions of mesh triangles) as well as a line model where segments of a neuron branch are represented by lines.

While the current implementation only supports a rat neocortex model, there is the potential to support visualization for different scientific datasets in the future as well, using the same gesture controls implemented here. Mind Explorer VR has the potential to be a useful tool in big data analytics and will be an engaging way for users to visualize and analyze large scientific datasets.

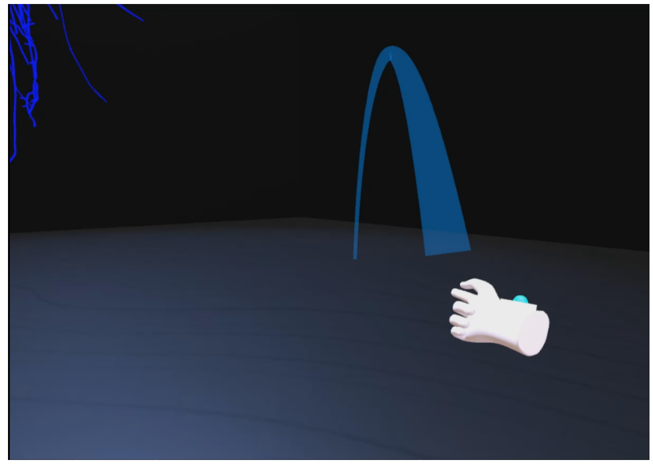

Figure 2: Screenshot of a user teleporting through the virtual scene.

3 DEMONSTRATION SETUP

Initially, the audience member starts with a down-sampled line representation of the neuron network model (the entire model is too detailed to fit into main memory). This initial view is shown in Figure 1. Using gestures, the model can be zoomed — using grabbing gestures and pulling the hands apart, panned/moved — by using a flat hand gesture and moving the hand as well as rotated — again, by grabbing hands but by rotating them.

Using virtual reality integration, users can explore a small virtual room that contains the model by changing the model — with the gestures described before — or by walking or using the teleportation system. Figure 2 shows the teleportation system which allows users to jump around the small room and change perspective as well as distance to the model. To teleport, the user points with the hand at the location they wish to move to.

After repositioning the audience member/user, panning, rotating and zooming the down-sampled model, the neural network can be analyzed in detail using three different operations as we describe in detail in the following sections. First, a subset/part of the model can be analyzed in higher resolution. To do so, the user interactively defines a spatial query and, upon execution, the very detailed subset of the model is retrieved and shown in virtual reality. Second, the connectivity of the model can be studied. For this, the user touches (or selects) a neuron branch and the entire neuron as well as connecting neurons are highlighted. Finally, the user can select a neuron branch and send messages along it. The messages are passed to connected neurons to show how electrical impulses propagate in the model.

The user can choose the different modes/analyses with a handheld menu in virtual reality as shown in Figure 3.

4 VISUAL ANALYSIS

Visual analysis of the entire surface mesh model of the neural network is not possible as it is too big to render in VR. Mind Explorer VR consequently allows users to perform user-specified spatial queries on the down-sampled line model of the neocortex in

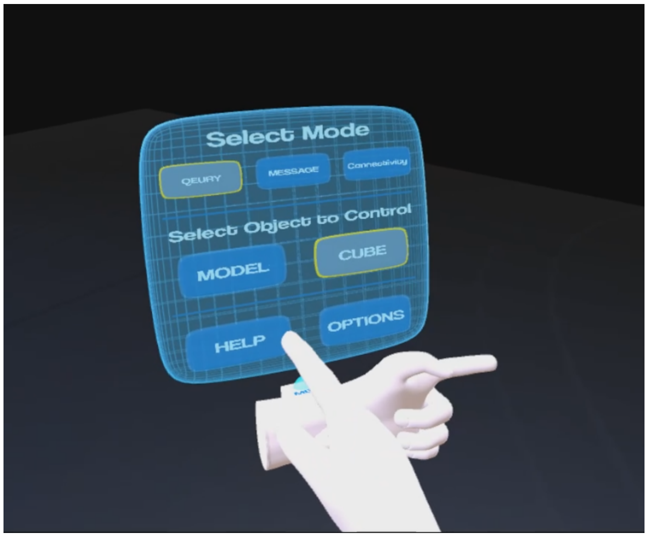

Figure 3: Control menu to choose different analyses in virtual reality.

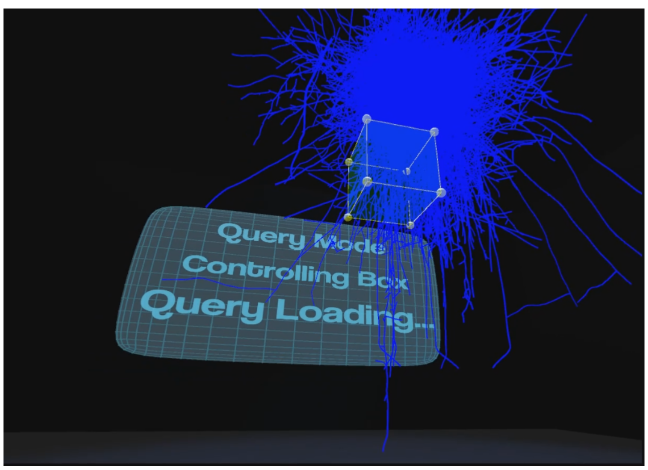

Figure 4: Screenshot of the query box (yellow borders) on the down-sampled neocortex model with blue coloured line neurons.

VR to retrieve and visualize the detailed mesh representation of the selected subset for closer analysis.

The initial definition of the spatial query is done on the down-sampled representation of the neocortex. The box representing the query can be moved, enlarged and rotated with the Manus VR gloves using the same gestures used to manipulate the down-sampled model of the neocortex. To pan, zoom or rotate the neocortex model, the gestures are simply done in the open (without grabbing any object) with the gestures described before. To pan, rotate or enlarge the query box, the box is grabbed and then the same gestures are used as for the model: grabbing and pulling apart to enlarge it, using flat hands to push it and grabbing and rotating the controllers to rotate it. Figure 4 shows the query box on the model in virtual reality.

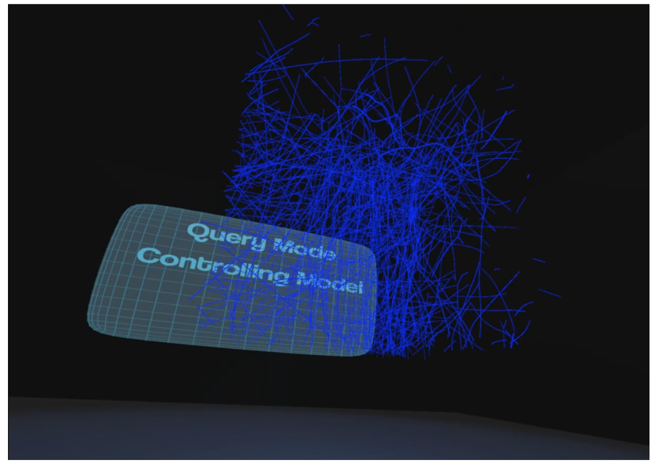

Figure 5: Screenshot of a query result. The resulting subset of the high resolution mesh surface model is rendered in three dimensions.

Once specified, the query is executed on the specified area of the neocortex, and a much more detailed version of this area of the neocortex is retrieved. Execution of the spatial query is performed using the FLAT spatial index [9]. It allows for rapid spatial querying of the large mesh model dataset.

The query result is a subset of the mesh model visualized in virtual reality and can again be analyzed in detail using the same hand gestures as before. Figure 5 shows an example query result, i.e., a subset of the mesh model. The detailed representation can again be queried, not to increase the level of detail further, but to retrieve different subsets of the subset of the neocortex.

A video of the spatial querying feature is available here: https://youtu.be/1LJTH16UVRY.

5 MESSAGE PASSING ANALYSIS

The user can use the message passing feature to analyze the connectivity of the neural network and, more importantly, to understand how electrical impulses are propagated through the network. From the initially selected branches, the messages are propagated to the rest of the network, traveling along the branches of the neurons. Messages will be copied when branches diverge and will also be copied to other neurons (as well as their branches) when they pass a synapse — the structure connecting two neurons and allowing electrical impulses to leap between them. Messages traveling through the network are highlighted by a change in color as is shown in Figure 6.

This analysis aims at enabling users to see how neural networks actually function, and how messages can be sent from single locations to multiple places in the network. Mind Explorer VR allows the user to configure number, length, and speed of the messages to make it possible to see message passing occur clearly on both a small, per neuron level and on a much larger scale across the entire network. Crucially, the user can also configure how synapses propagate messages, i.e., how likely they are to copy messages to

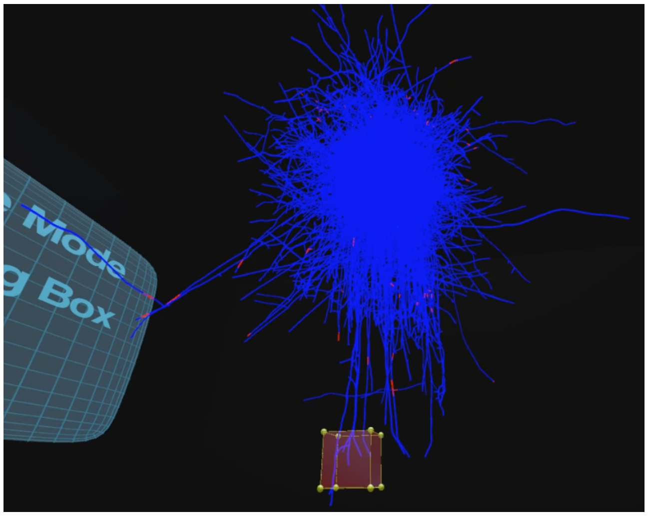

Figure 6: Screenshot of the neocortex model where messages are passed. The messages are red and highlight the location of where they currently are.

connected neurons, which enables to truly understand the properties of the network.

To initiate message passing, the user can select a box on the down-sampled model of the neocortex and messages will be initiated in all intersecting neuron branches. Selecting a branch is shown in Figure 6.

While (as well as before and after) messages are passed, the down-sampled neocortex model can be panned, zoomed and rotated with the gestures described before. A video of the message passing functionality is available here: https://youtu.be/7XxlsmhoZJw.

6 CONNECTIVITY ANALYSIS

With the final analysis, the connectivity of the neural network can also be analyzed and better understood. Also in this case, the user selects a branch by touching it or by selecting multiple branches by using a box (and all branches intersecting the box are chosen).

The selected branches are all highlighted, as are all other branches of their neurons along with all branches of neurons connected through synapses. An example of highlighted branches (in green) is shown in Figure 7 with the hand touching and thus selecting a branch (using the gloves).

The model of the neural network can be manipulated using the gestures described before.

7 CONCLUSIONS

As new virtual reality technology emerges, so do new and exciting applications for it. These are being seen in many different areas, such as entertainment, science and more. While some of these uses are novel and do not have much practical use, we feel that the visualization of large and complex data will truly benefit from virtual reality technology, and using it, we can overcome several flaws previous techniques of visualization have.

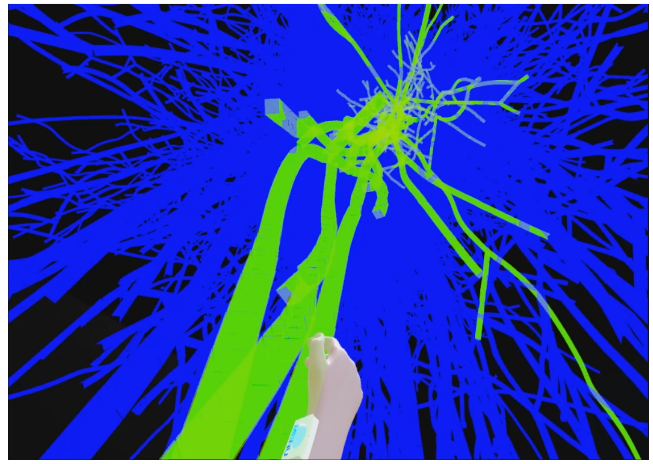

Figure 7: A screenshot of a connectivity analysis on the neocortex model. The connected branches and neurons are colored green.

Mind Explorer VR implements a novel way in which users and scientists can interact with data or, in this particular example, with a detailed model of a neural network. Putting the model in virtual reality, users can analyze the data using intuitive gestures. More precisely, they can increase the level of detail of the model and also understand the connectivity of the neurons in the model.

Mind Explorer VR furthermore demonstrates how to build general tools to interact and analyze scientific data to ultimately derive novel insight on a level that is difficult to achieve in traditional interfaces.

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