

Immersive Analytics of Multidimensional Volumetric Data

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Wien, 24. November 2020

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Kurzfassung

Das Verstehen und Interpretieren von volumetrischen multidimensionalen Daten ist eine komplexe und kognitiv anstrengende Aufgabe. Vor allem im Bereich der Materialwissenschaften ist die Exploration umfangreicher räumlicher Daten zwingend notwendig. Die zerstörungsfreie Prüfung (NDT) spielt in der industriellen Produktion vor allem im Bereich der Material- und Bauteilprüfung eine wesentliche Rolle hinsichtlich der Analyse, Visualisierung und Optimierung von neuen, hochkomplexen Materialsystemen wie Faserverbundwerkstoffen. Um die steigenden Anforderungen an diese Materialien und Komponenten der Zukunft in industriellen Anwendungen zu gewährleisten, sind umfangreiche Inspektionen und Kontrollen essentiell. Die durch bildgebende Verfahren wie Röntgencomputertomographie (XCT) generierten NDT-Prüfdaten umfassen neben 2D Bildern volumetrische Modelle, und daraus abgeleitete hochdimensionale Datenräume und können oft nicht, oder nur bedingt, auf Desktopmonitoren mittels Standard-2D-Visualisierungstechniken evaluiert werden. Daher wurden in dieser Arbeit neue immersive Visualisierungs- und Interaktionstechniken mittels Virtual Reality (VR) zur Untersuchung dieser hochkomplexen, heterogenen Materialsysteme entwickelt. Wir präsentieren eine neue Technik namens "Modell in Miniatur" zur effektiven interaktiven Exploration und visuellen Analyse der Faser-Charakteristiken. Weiters kombinieren wir verschiedene Ansätze wie Explosionsdarstellungen, Histogramme und Knoten-Kanten Diagramme, um einzigartige Einsichten in die Verbundwerkstoffe zu ermöglichen. Unter Einsatz körperlicher Interaktion und Navigation, und der Erweiterung der Fähigkeiten des Nutzers, sind bisher unmögliche Einblicke in komplexe Materialstrukturen möglich. Dabei setzen wir neue Erkenntnisse der immersiven Analyse ein, um die räumlichen Daten begreifbar zu machen und testen die Ergebnisse in einer qualitativen Studie mit Fachexperten. Die Evaluation unserer Techniken zeigt positive Resultate, die für einen Nutzen der immersiven Analyse von Verbundwerkstoffen und für die Exploration von allgemeinen hochdimensionalen Volumen spricht. Die gewonnenen Einsichten stellen damit einen wichtigen Schritt zur Weiterentwicklung zukünftiger immersiver Analyseplattformen dar.

Abstract

Understanding and interpreting volumetric multidimensional data is a complex and cognitively demanding task. Especially in the field of material science the exploration of large spatial data is crucial. Non-destructive testing (NDT) plays an essential role in industrial production, especially in the field of material and component testing, regarding the analysis, visualization, and optimization of new, highly complex material systems such as fiber composites. In order to support the increasing demands on these materials and components of the future in industrial applications, extensive inspections and controls are essential. NDT inspection data generated by imaging techniques such as X-ray computed tomography (XCT) include 2D images, volumetric models, and derived high-dimensional data spaces. They can rarely, or only to a limited extent, be evaluated on desktop monitors using standard 2D visualization techniques. Therefore, novel immersive visualization and interaction techniques using Virtual Reality (VR) were developed in this thesis to investigate highly complex, heterogeneous material systems. We present a novel technique called "Model in Miniature" for an effective and interactive exploration and visual analysis of fiber characteristics. Furthermore, we combine different approaches like exploded views, histograms, and node-link diagrams to provide unique insights into the composite materials. Using embodied interaction and navigation, and enhancing the user's abilities, previously impossible insights into the most complex material structures are possible. We use the latest findings from the field of Immersive Analytics to make the spatial data more comprehensible and test the results in a qualitative study with domain experts. The evaluation of our techniques has shown positive results, which indicate the benefits of an immersive analysis of composite materials and the exploration of overall high-dimensional volumes. The insights gained therefore represent an important step towards the further development of future immersive analysis platforms.

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Introduction

All truths are easy to understand once they are discovered; the point is to discover them.

– Galileo Galilei

In this chapter the underlying motivation of the thesis is presented. It briefly describes which topics are covered and how they are related. The resulting problems are highlighted and the goal of the thesis is presented. Finally, the further structure of the thesis is outlined.

1.1 Motivation

Tools that support the visualization of information are crucial in many scientific fields. The support of users in their demanding cognitive tasks, required to make decisions and understand complex relationships, is the primary goal. In a production-related environment, this support directly results in cost reduction, increased efficiency, improved flexibility and quality, and thus in a significant competitive advantage. An area, in which methods for visualization are of immense significance, is the field of material science. The development of new customized materials is highly complex and, due to the ongoing digitalization of the "Industry 4.0", relies on novel interactive visualizations for the manufacturing and inspection process [CS17, Ida19].

Non-destructive testing (NDT) plays an essential role in the analysis, visualization, and optimization of complex, heterogeneous material systems, such as fiber composites, in order to produce highly integrated and lightweight components in a cost-efficient way. The difficulty here is to carry out extensive inspections and tests on safety-critical components, that must not or cannot be damaged, hence the investigation must be

based on purely two-dimensional sectional images. These images can be obtained and analyzed using various imaging techniques. Additional secondary data can be obtained by applying segmentation and extraction algorithms. The analysis of this spatial and abstract information can often only be performed sufficiently by experts. This time-consuming and complex task can be made easier by visual computing. Due to new possibilities of NDT, volumetric models and high-dimensional data spaces are becoming more and more the basis of data analysis. These can often only be evaluated in a limited form or not at all, using 2D standard visualizations on desktop monitors. The inherent spatial structure including the extracted characteristics cannot be sufficiently reflected. For this reason, new techniques that go beyond conventional Visual Analytics approaches are required.

Current approaches focus strongly on numerical values represented in two-dimensional charts. The volume under investigation is usually presented in a small 3D view and values from statistical calculations are displayed in juxtaposed form. Since composite materials characteristics are high dimensional, often complex scatterplot matrices are required or dimensionality reduction methods are applied. All these methods and representations render the interpretation difficult, because they reduce the dataset to two-dimensional values and thus cause information to be lost. Since material data is inherently spatial, a three-dimensional representation is important to enhance the understanding and interpretability of the data. Therefore, alternatives to the current visualization methods for characteristics and feature distributions are necessary.

A new research field called Immersive Analytics (IA) aims to improve data understanding and decision making by new kinds of display and interaction technologies. With immersive technologies, such as Virtual Reality (VR), new interaction and visualization techniques have become possible, that were previously not feasible or even unimaginable. This enables a detailed understanding of highly complex internal structures and thus the optimization of heterogeneous material systems. Various studies indicate a trend that an immersive VR setup can increase classification accuracy and lead to a higher degree of engagement in the execution of various tasks. [FRFN18, SWKA19, KWO⁺20, HRD⁺19, WZYW20, IDJW19, SPO⁺19]. IA can therefore be used to gain previously impossible insights into fiber composites and their multidimensional characteristics.

1.2 Aim of the Work

The goal of this thesis is to develop a new way of exploration and interaction of spatial, multidimensional NDT volume data through Immersive Analytics. The main objective is to develop a VR framework, which allows the analysis of fiber reinforced composites within an immersive workspace. Thereby the spatial context of the volume data should be the primary focus and unjustified 2D visualizations should be avoided. The framework will be developed in cooperation with domain experts in the field of composite materials and evaluated by a qualitative study. As a result, the project contributes to recent Immersive Analytics research in the field of material sciences, by addressing questions of

what immersive technologies can offer in relation to Visual Analytics tools and how the space around the user can be effectively integrated into the analysis. In conclusion, the following research questions are addressed in this thesis:

- (Q1) How should an immersive workspace be structured to support the exploration of fiber reinforced composites?
- (Q2) Is it possible to enable the immersive exploration of fiber-reinforced composites utilizing only 3D spatial representations?
- (Q3) Which visualization and interaction idioms support natural exploration in the immersive environment?
- (Q4) Which interactions and visualization methods facilitate an overall view of the volume and a reduction of clutter?
- (Q5) How can spatial regions with similar fiber characteristics be identified in the immersive environment?
- (Q6) How can similarities between the spatial subvolumes be revealed?
- (Q7) How can a detailed comparison of fiber characteristics between subvolumes be shown?

The research questions formulated here are intended to identify which and especially where immersive technologies can be used efficiently. IA has only recently started to research design criteria that remove the barriers between people, their tools, and their data, and is still far from declaring finalised guidelines. Therefore, this thesis can only offer methods and examples to answer these questions, but cannot provide the one correct solution, if there is one.

1.3 Outline of the Thesis

The remaining chapters are structured as follows:

Chapter 2 - Material Science Background is dedicated to the field of Material Science and defines its relevant problems. It describes in more detail, which data is processed, how it is generated, and under which aspects it is analyzed.

Chapter 3 - Immersive Analytics Background outlines the research field of Immersive Analytics. We will explain its emergence and the paradigm shift that is connected with it. Furthermore, the advantages of Immersive Analytics and the perception of the users are discussed.

Chapter 4 - Related Work presents current attempts to visualize material data. We discuss the current shortcomings in the exploration on the basis of different applications.

For a better comparison of the used methods we will show examples from Visual Analytics as well as Immersive Analytics applications.

Chapter 5 - Methodology reviews our approach in more detail. We will describe each visualization and interaction technique that domain experts can use to explore the fiber data.

Chapter 7 - Results & Evaluation shows the typical workflow in an immersive workspace and demonstrates the resulting framework using a specific scenario. We also present the discoveries we have made through an evaluation with experts and novices from the field of material science. Their feedback and the results of a questionnaire will be evaluated and discussed.

Chapter 8 - Conclusions & Future Work finally concludes the thesis by summarizing what we have learned during the development of the framework. Inspired by this and the knowledge we gained by the feedback, we discuss possible topics for future work in this area.

Material Science Background

The objective of this chapter is to introduce the field of material science and explain the challenges it faces. In order to understand the approaches chosen in this thesis, the way in which the materials are examined is described. The primarily used imaging modality is explained and then the materials to be investigated are discussed in more detail. Furthermore, this chapter describes how domain experts work with composite materials and the high importance the field of visualization holds in this domain. Finally, the data used in this thesis is presented and their generation is described.

Materials Science deals with the manufacturing, analysis, characterization, and utilisation of materials. This field of science plays a critical role in modern industry to develop new materials and components for application-critical tasks. These adapted, robust, and high-tech materials are needed in a wide range of sectors such as health care, automotive, aerospace, agriculture, construction and many more. The goal is to develop new materials tailored to the respective requirements by analyzing and understanding complex materials, and thus staying ahead in the competition [CS17]. Various tests and imaging modalities are available to examine the different materials.

2.1 Examination of Material Data

The acquisition of data on materials and material systems can be done either by non-destructive testing (NDT) or destructive material testing (DT). In NDT, materials have to be analyzed in their current state without physical changes before testing. Since this usually prevents any view into the interior of the material, imaging techniques are of essential importance here. For a quick examination, 2D imaging techniques are mostly used to obtain data by digital extraction from the target material. These include modalities such as the cost-efficient 2D ultrasonic testing (UT), in which the propagation of sound waves is measured, or thermography, in which the material is measured under thermal change [CS17].

An important technique for the precise examination of materials is X-ray computed tomography (XCT). This imaging modality enables highly detailed representations of a wide variety of materials and has only recently been applied in industrial applications [BWW⁺17, CS17, Ida19]. Since XCT can be used for almost any material, its application is versatile, but is currently primarily used for metrology, qualitative inspections by NDT, and material characterization. To generate the data, the specimen is placed on a rotating plate between the X-Ray source and the detector. A series of 2D images of the sample is then taken at various angles. These penetration images are created by the X-rays that pass through the sample as a beam and are attenuated by the material. Passing through a special layer, the remaining X-rays are converted into light, which can be detected. The different images of the 360 degree rotation are then reconstructed into a 3D volume. The volume obtained from the XCT measurements consists of so-called voxels, whose grey values are related to the intensity of the measured light. The structure of the data acquisition process just described is demonstrated in Figure 2.1.

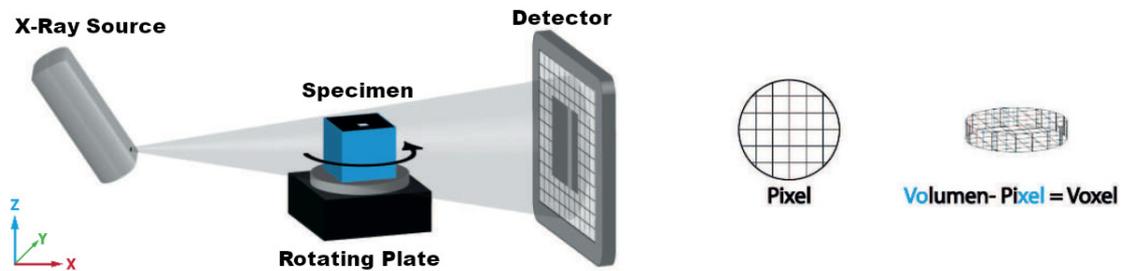


Figure 2.1: The image is taken and adapted from [JDMJ19]

For all the images, obtained from the measurements, additional secondary data can be derived. The supplementary information is calculated by extracting interesting features like pores, cracks, inclusions, delaminations etc. from the original imaging techniques. Any further details are calculated from the intensities encoded in the voxels. Secondary data can also be generated by combining several measurement methods or by simulations. For the extraction of this additional data, segmentation and feature extraction techniques as well as quantification and clustering techniques are required [CS17].

2.2 Fiber Reinforced Polymers

In modern industry, fiber reinforced polymers (FRP) are of great interest [AAS⁺16, BWW⁺17, WAL⁺14, CS17, RPML19, Ida19]. The strong demand is due to their promising and highly unique mechanical properties. For example, FRP offer an increased strength to weight ratio and increased stiffness compared to other conventionally used materials. Also properties such as a high level of durability, damping properties, bending strength and resistance to corrosion, wear and similar make this material of immense importance in demanding industries, where the stability of heavily loaded components is critical. As a result, industries such as medicine, automotive, and aviation industries are

particularly interested in examining the characteristics of these materials. The properties of the materials result from the manufacturing process. Composite materials are a combination of two or more material components, one of which is the basic material, the matrix, and the other is the reinforcing material, which can be in particle or fiber form. Therefore, the components being analyzed, which mainly define the mechanical performance characteristics, are the matrix, fibers, pores, inclusions, and voids. This means that fibers, matrix/fillers, as well as production-induced characteristics are important and have to be investigated.

In this thesis we focus on the largest and technically most prominent group of composite materials, the fiber composite materials. There are different reinforcing materials such as glass fibers, carbon fibers, polymer fibers, as well as cellulose fibers, which are usually injected into a matrix out of plastic. An overview of the different fibers is presented in Figure 2.2. Each of these fiber types have specific advantages and disadvantages and influence the composite material through its fiber content as well as its fiber orientation distribution and fiber length distribution. To determine these properties non-destructively, methods for visualization, abstraction, quantification, and general exploration of these XCT data are required.

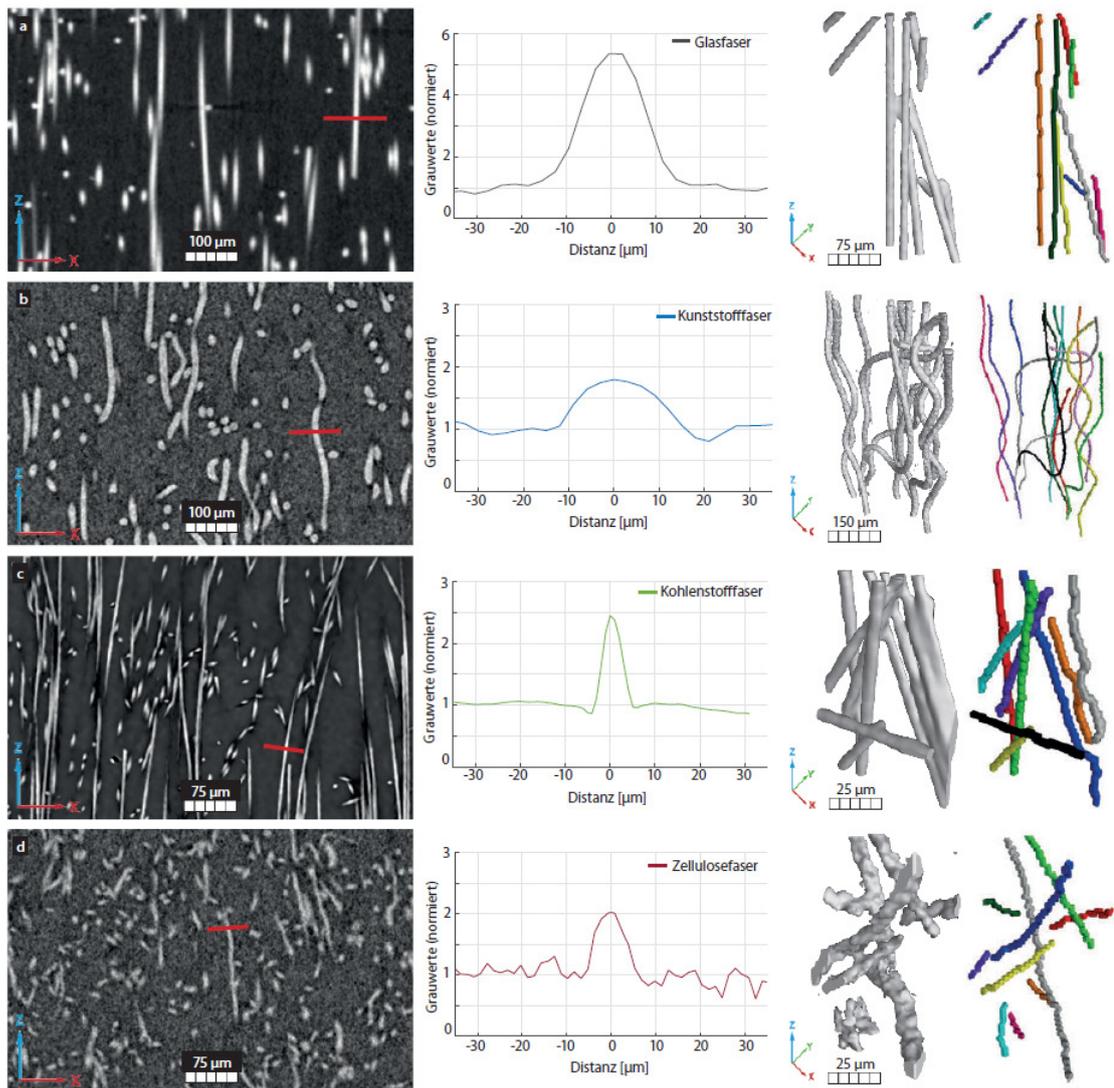


Figure 2.2: Overview of different fibers to reinforce the matrix material. From left to right there are shown two-dimensional cross-section images, the gray value gradient between matrix and fiber, and the rendered fibers. From the top to the bottom glass fibers, polymer fibers, carbon fibers, and cellulose fibers are presented. The image is taken from [JDMJ19].

2.3 Visual Exploration

As can be concluded from the sections described above, the analysis and evaluation of complex composite materials is of crucial importance for the development of new material systems. For quality management and inspection of materials, new visualization and interaction techniques are needed to enable innovative analyzes. Traditional visual

analysis approaches provide reliable results and allow the viewers the interpretation of multidimensional fiber data. Since the inherently spatial datasets are becoming increasingly complex, they cannot always be displayed effectively on two-dimensional monitors. Therefore, a new approach is required, in which the three dimensional fibers can be displayed in a more intuitive way. The research area of Immersive Analytics focuses on the facilitation of decision making through virtual representations. As can be seen from current publications, the number of VR systems is increasing, especially in research and development (34.4%), healthcare (25.8%), education (17.2%), and industrial (9.8%) sectors [MSMADM20]. Therefore especially in the industrial sector, there is still a lot of potential for the immersive exploration of spatial, multi-scalar, and multimodal NDT data. Examples for visualizations in the field of material science can be found in Chapter 4.

2.4 Material Data in this Thesis

As mentioned before, this thesis deals with fiber composites. Our work is focused on novel visualizations and interaction techniques in the field of Immersive Analytics to improve the production and analysis of composite materials. Our developed framework is able to visualize different fiber datasets of various fiber types and fiber quantities.

Our tool works with secondary data extracted from the fiber dataset of XCT scans. The fiber characterization pipeline (FCP) for creating the pre-processed dataset is based on the FiberScout module, by Weissenbock et al. [WAL⁺14], of open_iA [FWS⁺19]. In this process, a specimen is scanned using XCT and a volume dataset is reconstructed from it. Fibers are then detected using filters and segmentation algorithms. A labeling filter is then applied to the extracted fibers to assign the individual voxels to a unique label. Afterwards the calculated fiber characteristics are stored in a comma-separated values file (.csv). This file contains for each detected fiber its start and end coordinate value and additional features, like length, diameter, volume and orientation. In total, up to 25 attributes can be calculated and stored. Our tool uses this secondary data to visualize the fibers as cylinders and enable an exploration through the complex composite material.

Immersive Analytics Background

This chapter deals with the basic principles and aspects of the research area Immersive Analytics (IA). It provides a background of its emergence and describes its opportunities and advantages for the analysis of data. Finally, the influences on perception as well as the relevance in this thesis are discussed.

3.1 History and Objective of Immersive Analytics

The objective of IA focuses on the research of new user-interface technologies to remove barriers between people, their data, and the tools they use for analysis. This should enable new perspectives on complex data, processes, and problems that can be explored through natural interactions. As a result, IA draws on several disciplines such as data visualisation, Visual Analytics, virtual reality, computer graphics, and human-computer interaction (HCI) [Mar18, Chapter 1][CCC⁺15].

With the desire to make the interface between user and machine more intuitive and efficient, HCI can be seen as a starting point for this development towards IA. HCI aims to create new ways to integrate computers into our work and our lives by driving developments in interaction technologies. At the same time the graphics research rapidly evolved and in combination with novel input devices, advanced graphics hardware and real-time rendering techniques first VR systems, like the Cave Automatic Virtual Environment (CAVE) [CNSD⁺92], emerged. During this period, it was of major interest to study spatial data in this new medium. With the evolvement of Information Visualization, the focus on 3D representations of abstract data shifted away to applications, which emphasized standard desktop and WIMP (Windows, Icons, Menus and Pointers) interfaces on 2D monitors. This is partly due to the fact that, in the early 90s, screen resolution was too low for a really convincing virtual reality experience. Due to ever increasing data sizes and the attention to human cognition, the field of Visual Analytics emerged. With it, the quality of consumer-class immersive systems has also improved and reached a

sufficient level of resolution and usability. With the need for new interaction paradigms and data visualizations to achieve explorations beyond desktop computing the Immersive Analytics community formed.[Mar18, Chapter 1][CPP⁺17, CCD⁺17]

The step towards new display and interaction technologies results in more natural input mechanisms as well as in a richer and more embodied data analysis experience, which were impossible with traditional desktop computing environments. The ability to perform analysis on larger visual spaces, whether virtual or physical, can support discoveries and insights everywhere by everyone, both working individually and collaboratively. The act of working in an environment, which consists in navigating through it and managing the space itself and the objects it is occupied by, is central to human cognition. By using the space around us and interacting in a more natural way, we improve decision making on complex data that would otherwise exceed our ability to correctly interpret them [Mar18, Chapter 1][CCD⁺17, CBL⁺17, BCC⁺19].

The concept of IA can be applied in various applications and is not limited to one specific technology. Nevertheless, a trend towards Mixed Reality (MR) technologies like VR and Augmented Reality (AR) is clearly visible. These new media promise a more immersive setting as they use novel display and input technologies along the reality-virtuality continuum to enable a credible 3D environment. Opportunities arise from the utilisation of 3D stereoscopic vision, high resolution, and head tracking, factors that greatly influence immersion in Virtual Reality Environments (VRE). This effort is supported by other technologies like sensory output, which could be a haptic display, olfactory display, or smart textiles [NSL⁺19]. Further improving the capabilities of the output devices, like a larger Field of View (FoV) or a higher resolution, has an effect on the results. Also additional sensors, which support a more natural interaction, like the navigation with the user's own body or real-world gestures, for example grabbing or touching a virtual object, have a great impact on immersion. Other possible input mediums would be the usage of voice input, eye-tracking, or even physically touchable devices. Each of the currently used immersive systems [CCC⁺15, AGHWK16] support different aspects of the visualization and analysis process. The CAVE2 [FNT⁺13] as an example, has advantages in collaborative applications with several users, but a big enough room is needed. Further, only one user gets the additional correct immersion through head tracking. HMDs like HTC Vive [Viv] or Oculus Rift [Fac] suffer from smaller FoVs and are tethered to a desktop machine. However, they have the benefit of individual head tracking and are simpler to set up than CAVEs. AR devices like the Microsoft HoloLens [Mic] enable to see the physical surrounding of the user and to augment it with additional information and visualizations, but have drawbacks regarding occlusion and color fidelity [Mar18, Chapter 1][CCC⁺15, BCC⁺19, SPO⁺19, WSS20].

The concepts of IA offer many opportunities that go beyond traditional Visual Analytics. The first opportunity is *situated analytics*. Here the goal is to augment the physical world with additional abstract data. This way an analysis can be supported or guided at the place of use. The discovery of important patterns can be enhanced by linking real objects with virtual information. Another opportunity is offered by *embodied data exploration*,

which exploits the increased engagement of the user by immersion. The natural movements of the user are used for the exploration and extended by virtual abilities in the immersive environment. This reduces the cognitive work of the user, as the exploration feels more natural than through mouse and keyboard input. A third opportunity comes from *collaboration*, which uses immersive technologies to improve collaborative work, especially over long distances. Here the combination with embodied data exploration enables a more socially engaging remote collaboration and eliminates the need for experts to be on site. Another opportunity with high impact arises from *spatial immersion*. This provides the possibility to use an almost infinite, three-dimensional virtual workspace for analysis. This setting and the process of organizing and working in it, is standard for analysts and therefore mimics their usual analytical approach. In the initial phase of an investigation, an effort is made to get a "feeling for the data". Spatial immersion uses human 3D perception and spatial cognition skills to get a more profound visual understanding of the underlying information. A fifth opportunity is *multi-sensory presentation*. As already mentioned, IA is not bound to a specific technology, therefore other human senses besides vision can gain a user additional insights. For instance, sound and smell can be used to convey abstract data, which can lead to a more in-depth experience. Lastly, increased *engagement* is an important opportunity in IA. With environments that become more and more credible and interactions that are adapted to human behaviour, the application becomes more intuitive and natural, thereby integrating the user into the virtual augmented world. This enables data-driven narratives that involve the user cognitively and emotionally, which can be seen as a new way of communicating information through a convincing environment. With this immersive experience, exploration becomes more enjoyable and is seamlessly integrated into the analyst's workflow, increasing user engagement [Mar18, Chapter 1][CCC⁺15, CPP⁺17, SPO⁺19].

In summary, IA offers many opportunities that benefit from the greater freedom of the virtual environment and the extra dimension. Nevertheless, guidelines are needed to exploit these new possibilities for the visualization of various (abstract) data. These evidence-based guidelines will also help to address the debate on 2D vs. 3D visualization. We need to focus on designing immersive data representations to better understand, which representations are better suited for which tasks. This is certainly a good approach to determine when immersive analysis techniques are useful and to avoid the "unjustified use" of 3D representations, as Munzner [BM13, Mun14] warned. One of the key questions and opportunities for future IA research is not about whether 2D or 3D visualizations are more effective, but how the space around the user should be used to display additional information and support an engaging sensemaking process [Mar18, Chapter 2][CPP⁺17].

3.2 Benefits for Visualization and Analysis

Since IA offers promising opportunities, researchers recently started to investigate them in various application areas. The benefits, of why one tries to make use of IA can roughly be found in the following explanations:

- **Engage the user** – Immersive systems manage to recreate a real world experience by cleverly exploiting depth cues. Representations, in which depth information is used have an engaging effect, resulting in a positive impact on data analysis tasks. Studies have also shown that users preferred 3D visualizations even in scenarios, where task effectiveness did not improve [Mar18, Chapter 2]. The authors Bluff and Johnston [BJ19] use this effect for new engaging interactions. They give the users a feeling of "presence" by providing them with control over their environment and its scaled-down version. Furthermore, they equip the users with "god-like" abilities, that allow them to manipulate the world, its structure, and even themselves, through which they can explore and create new unique interactions. In the work of Ivanov et al. [IDJW19] the immersive environment is used to create a unique atmosphere for data-driven storytelling. The authors allow the users to examine the data of mass shooting incidents in the United States by immersive unit visualizations. Unit Visualization is concerned with representing each element of the data set as an individual visual object in the given environment. Through dynamic transition between overview and details the users can view the avatars and their stories, which creates an affective personal experience with the data.
- **Using depth to show an additional abstract dimension** – Technologies such as VR and AR support the unique advantage of leveraging the third dimension and perceiving it more correctly via stereoscopic rendering. Still, there is little empirical evidence, which visualization methods are effective for immersive displays. Current studies indicate the advantages 3D scatter plots, histograms, node-link diagrams and similar have in immersive environments, as many perception problems common in desktop setups are avoided. The study of Whitlock et al. [WSS20] showed that participants used their body to measure size, height, or depth, which makes depth a viable channel to encode data. Depth became therefore more effective as tasks were completed faster. As long as only two attributes with a position have to be displayed, a two-dimensional space on a monitor screen is sufficient. As the number of dimension grows, dimensionality reduction (DR) techniques are needed. These are methods like Principal Component Analysis (PCA) or Multidimensional Scaling (MDS), which map high dimensional data to two dimensions. The more the data dimensionality is reduced, the higher is the information loss and therefore potential misinterpretation in the visualization. By having an additional dimension, less information is lost. The authors Kraus et al. [KWO⁺20] compared scatterplots in different settings (2D/3D on a desktop screen, 3D in a VRE). They came to the conclusion that a VRE is beneficial for cluster identification tasks, as it increases memory and orientation capabilities. It turned out that the gain in overview is advantageous, but detailed information is more difficult to extract exactly.
- **Views on non-flat surfaces** – With the opportunity to be independent from conventional 2D monitors, visualizations on non-planar surfaces are possible. This means that new views on complex data are possible by mapping datasets with cyclic dimensions or without natural boundaries to spheres or cylinders. The authors

Yang et al. [YJD⁺18] investigated this approach by visualizing geographic maps in VR. They tested the effectiveness of different map projections and distortions on 2D planes and 3D spheres and came to the conclusion that an exocentric globe or curved map outperformed a standard flat map for some tasks. For network visualization techniques, an egocentric view can be useful [Mar18, Chapter 2]. Englmeier et al. [ESBH19] used this approach in combination with a tangible spherical object. They mapped geographical visualizations, node-link-diagrams and 360 degree videos to this sphere, with which users could interact.

- **Arranging multiple views in 3D space** – As described earlier, one of the opportunities of IA is its theoretically almost infinite work environment. This enables the analyst to use the entire area for their analysis process and to retrieve visualizations placed in it, based on human spatial memory [CPP⁺17]. The possibility to arrange views in 3D space allows for a more intuitive exploration and an embodied navigation between them. A study from Raja et al. [RBLN04] indicates that 3D data visualization techniques like 3D Scatterplots or 3D Histograms can benefit from head tracking in an immersive environment due to a greater spatial understanding of the entire dataset. Bento Box from Johnsons et al. [JOR⁺19] is a VR visualization and 3D user interface technique for comparative analysis of data ensembles. They display ten instances of time-varying simulations of blood flow juxtaposed in a grid arrangement at the same time in the VRE. The authors Liu et al. [LPED20] recently evaluated the layout design of small multiples in VR. They conclude that a curved design space is promising for a large number of small multiples and efficiently utilizes the space.
- **Visualising abstract data with a spatial embedding** – Rather than merely making use of virtual spaces to display multiple 3D visualizations, the position in space can now be used explicitly to enhance inherently spatial data with additional abstract information. Choropleth maps, prism maps, or even space-time cubes with their 2D geographical positions can be used in a natural way, but the third dimension will extend the spatial data with additional abstract information [Mar18, Chapter 2]. These Virtual Reality Environments (VRE) address long existing perceptual and interactional limitations of three-dimensional data representations, for example by removing occlusion by moving the head around a visualization [FFN19]. The advantage of viewing spatial data perceptually correct facilitates their understanding immensely. With the reduced cognitive effort it is then possible to extend the information content additionally by abstract information. This concept of combining object, space, and information to make complex systems easier and more naturally understandable is called Information-Rich Virtual Environment (IRVE) [Mar18, Chapter 2][PBN11, SPO⁺19]. The goal here is to find methods and possibilities for the user to get additional information from the environment and its objects. Therefore, the environment is extended by abstract information such as text, multimedia, or visualizations, which are inherently connected to the spatial data, but not directly perceptible in the physical world. This includes, for

example, the exploration of medical volumes, the labeling of certain features in biological objects, or the highlighting of specific relationships in documents. A possible approach is shown by Hurter et al. [HRP⁺17], where the movement of the user decides, depending on the visualization method, the strength of a filtering or the details of a graph network. More examples of applications, which utilize the spatial structure of their data can be found in Chapter 4.

In summary, in the field of immersive analysis, there is no single visualization technique suitable for all possible application areas and datasets. Much is still unknown in terms of design guidelines and the usability of Immersive Analytics depends on how the currently developed visualisation idioms and interaction techniques are applied or adapted. Still, there are at the moment some indications that 3D representations of terrain, networks, or multidimensional data generally have the advantage of providing a better overview and orientation of and within the structure, while 2D representations allow the user to more precisely manipulate, measure, or compare specific data [Mar18, Chapter 2].

3.3 Immersion, Presence, Engagement, and Perception

The combination of 3D spatial information with abstract 2D/3D data is essential for the effectiveness of IA applications. Furthermore a great impact is caused by the perception of the user and the psychological feeling of being in a different place than where one is physically present at the moment [Jer15, Chapter 4]. This feeling is created by immersion. The way the stimuli are generated for the user and the way they are interpreted by the user have to be treated differently and taken into account when designing a system. As result immersion can be divided into its technological aspect, in terms of the display technology and the sensory output used, and its psychological effect, in terms of how the individual perceives and interprets the presented stimuli [Mar18, Chapter 2][Jer15, Chapter 4][BCC⁺19].

3.3.1 Technological immersion (Presence)

Technological immersion focuses on the characteristics of the technology and the generation of a sense of presence. The goal is to offer a sensory experience that is as similar as possible to the real world, providing the sense of "being there". Different features [Mar18, Chapter 1][Jer15, Chapter 4] of the technology affect the objective degree of immersion.

- *Extensiveness* is concerned with the number of channels used for the extensive experience. It has an impact on the sensory inputs to the user, such as visual, acoustic, haptic, and similar channels.
- Proprioceptive *Matching* addresses the correct reproduction of physical interactions and the own appearance in the virtual world. Also the representation of other entities in the VRE affects the immersion.

- *Vividness* and *Surroundness* deal with the quality of the simulated environment. Key values are a wide field of view, high frame rates and resolution, as well as 360 degree of tracking.
- *Inclusiveness* is concerned with the extent to which the virtual world masks the real world.
- *Interactability* is an important concept, which can be divided into autonomous action and plausability. This feature describes the user's ability to interact autonomously with the world and influences the surrounding. The environment or the virtual entities should then respond to the action with real-world behaviour.
- *Communication channels* should allow for verbal and nonverbal ways of conveying a message.
- *Plot* decides how a story is introduced and how convincingly the other features are combined to enable an immersive experience.

The features discussed here are intended to increase the feeling of presence. Because presence is an internal psychological state, it is utterly subjective and cannot be guaranteed by technological immersion. The experience of presence is limited by technological immersion, which creates a form of illusion, in which the user attempts to not perceive the technology, but the environment it represents. Presence can be classified into four components based on the intended illusion [Mar18, Chapter 1][Jer15, Chapter 4].

- *Spatial presence* To create the illusion of being in a stable spatial location, the stimuli provided must create the impression that the virtual objects and entities are present in their physical form. The feeling of not only having seen the world, but having visited it, can be destroyed by external conditions known as break-in-presence.
- *Social presence* Social presence occurs when the user perceives communication with other virtual entities (both human and computer controlled) as realistic. A realistic representation of the other character is beneficial, but not necessary. What counts is the psychological involvement in the form of verbal or non-verbal actions between the characters.
- *Self presence* The illusion of self-embodiment is characterized by the perception of oneself. A virtual body, which is in line with ones own movements, improves the felt presence considerably.
- *Physical presence* To experience the virtual world as realistic as possible in the long term, an illusion of physical interaction is needed. By integrating feedback in the form of haptic interaction, sound, or even smell, the feeling of presence can also be induced during the exploration of the environment.

3.3.2 Depth Cues

Spatial immersion and the state of presence rely on human perception. The way we perceive spaces, shapes, and distances depends on depth cues. The efficient use of these cues enables a perceptually convincing virtual environment. This becomes highly apparent when creating qualitative 3D visualizations or when placing them in the space around the viewer, since the correct depth perception is strongly connected to the use of complementary depth cues [CPP⁺17]. Some of these depth cues, which have the potential to improve task effectiveness for certain types of visualization tasks, are listed below [Jer15, Chapter 9][Mar18, Chapter 2]:

Pictorial Depth Cues

- *Occlusion* is the strongest cue and provides relative distances between objects. The accuracy depends on the number of objects, as closer objects hide more distant ones.
- *Linear perspective* is based on the projective properties of the eye, which causes parallel lines to converge in the distance, in the so-called vanishing point.
- *Relative/familiar size* is the phenomenon, if two objects are of the same physical size, the object further away from the observer projects a smaller image into the eye. If the users can see their own bodies in the virtual world, this not only increases their presence, but they can also use their size as a relative reference.
- *Shadows/shading* provide a good indication of the height and depth of an object and its shape, which is reflected by the shadow cast.
- *Texture gradient* refers to the way how spatial patterns of objects will appear more dense at the distance like in linear perspective.
- *Height relative to horizon* is the phenomenon that objects appear closer the further away they are from the horizon, based on the assumption that the space is flat and the objects rest on the ground.
- *Aerial perspective* arises at very large distances from the observer due to light scattering in the atmosphere. This changes the color properties (e.g., hue, saturation, brightness), which causes near objects to appear with more contrast.

Motion Depth Cues

- *Motion parallax* refers to the effect that objects at different distances move in different magnitudes. This effect is utilized in VR by manipulating the point of view, because objects closer to this point (and the field of view around it) move faster and appear more blurred.

- *Kinetic depth effect* enables the acquisition of the three-dimensional shape of an object through its movement. For example, the change of a shadow can provide information about the geometry of the object.

Binocular Depth Cues

Binocular disparity is the phenomenon that both eyes produce largely similar optical images, but from slightly different angles. Binocular stereopsis happens when the brain interprets the depth and shape of objects through combining the disparate images. These binocular effects are reproduced in HMDs in *monocular* form (one image for a single eye), *biocular* form (two identical images, one for each eye) or *binocular* form (two different images, one for each eye). The biocular design might suffer from subtle conflicts in motion parallax, the binocular design is more complex and offers stereopsis, but can suffer from vergence, accommodation, and disparity conflicts.

Oculomotor Depth Cues

- *Vergence* is an important depth cue in the range up to two meters. Thereby, both eyes rotate simultaneously in opposite directions (convergence and divergence) to enable sharp vision.
- *Accommodation* refers to the eyes ability to change their curvature in order to focus on objects at different depths. This physiological effect blurs objects that are too far away from the optimal depth of field.

Contextual Distance Factors

- *Intended action* implies that two people can perceive the same world differently based on their actions. For example, an object out of reach can appear closer by using a tool that reduces the distance than without. These actions can also manipulate the observers current viewpoint and change their perception of the virtual space.
- *Fear* influences spatial perception by increasing the sense of height, causing the user to overestimate certain situations.

The efficiency of these depth cues strongly depends on the distance of the viewer to the observed object. The so-called personal space can be defined within arm's reach of the observer (about two meters). In action range (about 20 meters) around the viewer, in which the observer interacts with other people or objects, the action space is defined. Everything beyond that causes rather small changes in the depth cues and is called vista space. A ranking of certain depth cues by their importance for the perception of distances in different spaces can be seen in Table 3.1.

Depth Cues	Space		
	Personal Space	Action Space	Vista Space
Occlusion	1	1	1
Binocular	2	8	9
Motion	3	7	6
Relative/familiar size	4	2	2
Shadows/shading	5	5	7
Texture gradient	6	6	5
Linear perspective	7	4	4
Oculomotor	8	10	10
Height relativ to horizon	9	3	3
Aerial perspective	10	9	8

Table 3.1: Most important depth cues ranked in order of strength based on the classification of Jerald [Jer15, Chapter 9]. A ranking of 1 means that this visual cue is the most important for the given space. The personal space is about two meters from the viewer, the action space is up to 20 meters around the viewer and the vista space is everything in far distance.

3.3.3 Psychological immersion (Engagement)

Like the state of presence, engagement is also a subjectively perceived experience. Engagement can be associated with the condition of a flow, an enjoyable subjective state, in which people are fully engaged in a task (e.g., while working or watching a movie) until they forget their surroundings and everything around them except their task [Mar18, Chapter 1]. The use of this effect is important to improve the analytical process. Through the immersive environment an engaging effect can be created, where the users are extremely focused on their tasks and lose track of space and time. IA applications that provide this immersive workspace, in which the users are emotionally integrated, will result in a higher level of concentration that will facilitate decision making.

3.4 Impact on Thesis

Our project focuses on the immersive analysis of complex material data. The main goal is the development of a framework that enables the exploration of inherent spatial data in a virtual workspace. For this purpose a VR HMD, the *HTC VIVE Pro Eye* [Viv] is chosen as immersive technology.

In this project VR has several advantages over the other mixed reality technologies. First, HMDs like HTC Vive and Oculus Rift offer an affordable and commercially available option to create IA experiences [AGHWK16, CPP⁺17, BHM⁺18, BCC⁺19, FP19]. This allows the usage not only for individual experts or large research institutions with higher

financial resources. This enables students and pupils as well as interested users from other areas to use the system. Second, the increasing use of this technology makes it more intuitive for most users, as they may already have experience with it. The use of gesture control was avoided because technologies like the Leap Motion [Ult] are not very robust and can break the immersive feeling. The results of Filho et al. [FFN19] also indicate that the Vive controllers facilitate a lower learning curve and are more robust in their use. Compared to AR, VR was also chosen because it performs significantly better in terms of field of view and resolution. AR also has a disadvantage with color-based visualization methods because it provides less color fidelity [BCC⁺19, WSS20].

Immersive Analytics is a promising research area for visualization techniques in material science. Since the data always has a physical reference, spatial immersion can be used. Furthermore, the data to be investigated is typically highly complex and multidimensional, which requires both an overview for hypothesis finding and detailed exploration. Here is the problem that many of the techniques currently used to study the materials are complex and difficult for non-experts, as they rely on desktop monitors using standard 2D visualization techniques. To make the high-dimensional data spaces of secondary NDT data comprehensible and get insights into the heterogeneous material systems, novel techniques from the current research area of Immersive Analytics needed to be developed and analyzed in this thesis.

As discussed in more detail in Chapter 4, there have recently been a growing number of publications on the use of IA. Since the development of completely new visualization and interaction methods is not trivial, many studies deal with the adaptation of well-known visualization techniques. Most researchers continue to focus on visualizations for flat 2D monitors and transfer them into three-dimensional space. This thesis aims to avoid "unjustified" 2D visualizations in immersive environments and to put more emphasis on the leverage of spatial properties of space and data. Thereby some concepts and approaches of Information Rich Virtual Environments are used, in which relationships between objects, space, and information are fused together to enable new exploration [PBN11]. This is especially useful, as in material sciences structures and specific locations have certain characteristics, which can be enhanced with abstract information. Skarbez et al. [SPO⁺19] have given this concept the name Immersive Space to Think (IST) with respect to the immersive environment, in which the exploration takes place. The immersive workspace, which is developed in this thesis should provide an engaging, effective environment, which uses the spatial immersion to enhance humans natural cognitive skills.

Since most of the work is done in a seated position, this immersive working environment must be adapted to the needs of the analysts. The application should be able to be used by the expert both being seated or moving within a certain area. A standing or moving exploration should facilitate a natural interaction and support the users in their unrestricted discovery. Since professionals spend most of their time in an office with limited space that is often shared with colleagues, it is important to facilitate their, in some cases time-consuming, analyzes through less exhaustive interactions [CPP⁺17, FP19]. Extensive gestures with the arms or walking on the spot is very exhausting for longer

explorations and therefore not feasible for daily work. Seated operations with data manipulation techniques that work at arm's length can offer reduced fatigue. In this thesis we renounce finger gestures as unnatural or complex behaviors can lead to user confusions. Still, we combine the benefits of input controls with natural real world interaction metaphors, to lower the cognitive load on the user. With these approaches an immersive and engaging exploration of complex data is possible and can lead to new insights in the exploration of spatial, multi-scalar and multimodal NDT data.

Related Work

Chapter 4 is broadly divided into three parts. Section 4.1 explains the organization of the Related Work in more detail by means of the problems and research questions identified in this thesis. Accordingly, Section 4.2 describes the analysis and presentation of 2D and 3D spatial data both generally and in the material science domain. Section 4.3 shows new developments in the field of immersive analysis using multivariate data. Examples of data are shown, which obtain their spatial representation from the context of virtual space, as well as data which are inherently spatial, such as volumes from the fields of materials science or medicine.

4.1 Current Approaches and Issues

The field of information visualization and Visual Analytics aim at developing visual representations and methods for abstract multidimensional data. The user should be supported in the cognitive task to form hypotheses. With the first unsuccessful 3D representations, information visualization researchers became more conservative and doubted the usefulness of these representations [Mar18, Chapter 1, Chapter 2][CPP⁺17, SWKA19]. Through IA the mapping and visualization of data, whose semantics are inherently given, abstract, or even arbitrary is possible in a way that complies with the natural perception of humans. With evidence-based guidelines we can put the 2D vs. 3D debate aside and identify which representations enhance data understanding of spatial as well as static or abstract data in an immersive environment.

The design of new visualization techniques is not simple and the lack of experience, about the advantages and disadvantages of three dimensional visualizations, makes their development difficult [CPP⁺17]. Our thesis addresses the issue that current IA applications just extend basic techniques to 3D, such as bar charts, scatterplots, polar plots, parallel coordinate plots and other techniques mainly developed for 2D monitors. IA should focus on the spatial characteristics of the data and the immersive workspace,

to enable the discovery of still unexpected insights. Especially in the field of material science, inherently spatial data are available, which are enhanced with abstract data, where IA offers the possibility to explore such complex data in a more natural way than through Visual Analytics. The aim of this thesis is to visualize high-dimensional volumetric data of material science and to augment these structures in virtual space with additional abstract information. As result, the cognitive load of the users is reduced and their spatial orientation is exploited. For this reason, in Section 4.2 some currently used approaches to analyze multivariate volumetric data in general or from material science are presented. For all introduced applications the numerical values are the main focus. The representations of these values are slightly different, but still the spatial component of the data is not given a high priority. In many cases only a small 3D view of the volume is displayed, which is not always used for further interaction. In addition, statistics are evaluated over the entire volume and region-specific distributions can either not be visualized at all or only in a cumbersome process. As a result, a lot of information, which can be perceived through an object's spatial structure, is lost and the user has to rely on more precise, but numerical values.

The section 4.3 provides many recent approaches to visualize multivariate abstract data with Immersive Analytics. IA applications often gain their spatial component by placing a diagram in the three-dimensional workspace, but do not use data with a spatial structure embedded. Furthermore, there are several examples that use depth to add another dimension to the well-known diagrams. In 4.3.2, the last part of Section 4.3, there are a few works listed that explore volumes in an immersive environment. Since there are not many studies in the field of material science, a recent work from the field of medicine is presented here, which visualizes brain fibers.

4.2 Visual Analytics

Since the focus is on the general structure of Visual Analytics applications and not on specific techniques, the goal of this section is to present typical tasks and workflows and not specific algorithms. For this reason, both open source systems and proprietary platforms are presented here.

4.2.1 Multivariate Volume Data

The first application that meets the aforementioned characteristics is ParaView [Kitb]. This open source software platform allows the user to analyze and visualize data from different domains. The system offers explorations of and calculations with scientific data from areas such as Structural Analysis, Fluid Dynamics, Astrophysics and Climate Science. ParaView uses the Visualization Toolkit (VTK) [Kitc] and Qt [QTC] to achieve a multi-platform data analysis tool.

The core structure of the system is shown in Figure 4.1. It consists of a pipeline browser and a properties panel on the left side. Here the user can apply various filters

such as contouring, thresholding, slicing, cropping, or extracting connected components and change their properties. In the center of the interface the so called views are arranged, which are also shown in Figure 4.2. In these views the results of calculations or measurements are displayed in different diagrams like line plots, bar charts, or as 3D representations in the form of surfaces or volumes. In order to better understand complex data relationships, the diagrams can be linked via selection. These linked views help to find certain features in 3D volumes. The direct exploration of the volume itself suffers from the difficult interaction via mouse and keyboard.

Another application is called 3D Slicer [FBKC⁺12] [Sli]. This open-source software platform supports researchers particularly in the exploration of medical data. The system uses the Insight Toolkit (ITK) [Kita] for segmentation and registration of medical image data and VTK for presentation of the analysis techniques. The interface is also based on the Qt toolkit in this case. An example of the graphical user interface (GUI) can be seen in Figure 4.3. The structure can be adapted by the users to their tasks, in the form of specific layouts. Depending on the required use case, a comparative structure can be chosen with several separate 3D volume viewers or a layout can be selected for the quantitative comparison with chart viewers in a juxtaposition. To manipulate or adjust the loaded volumes, 3D Slicer uses several modules. As can be seen in Figure 4.3 on the left side, in the module GUI panel different modules for specific tasks can be loaded and their usage can be viewed. Possible operations include image filtering, intensity-based registration, segmentation, and more. These operations can be applied to three-dimensional datasets from different imaging modalities (e.g., CT, positron emission tomography (PET), magnetic resonance imaging (MRI) or ultrasound). The representation and comparison of several views of a volume are shown in Figure 4.4. Here the exploration of the quantitative parameters of a prostate dataset is shown. It can be seen that although the dataset is inherently spatial, the representation is difficult to comprehend without previous knowledge of the anatomical structure of the organ.

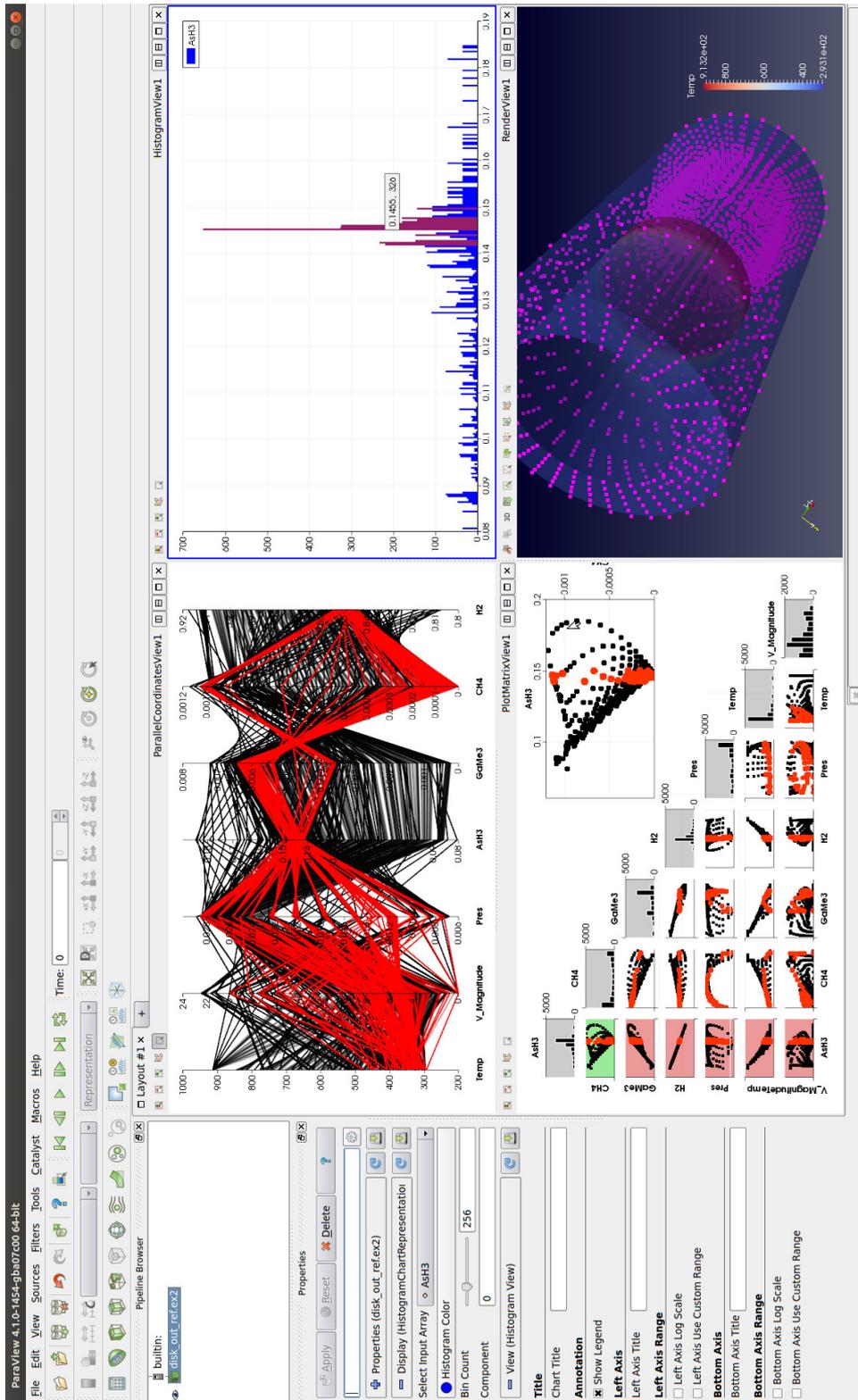


Figure 4.2: Paraview: Different views of the data are presented and the user selections are highlighted in red in all views. As can be seen, the visualization types include scatter plots, multiple coordinate plots, histograms and also 3D renderings. The linked selections are present in the various representations. The image is taken from [Kitb]

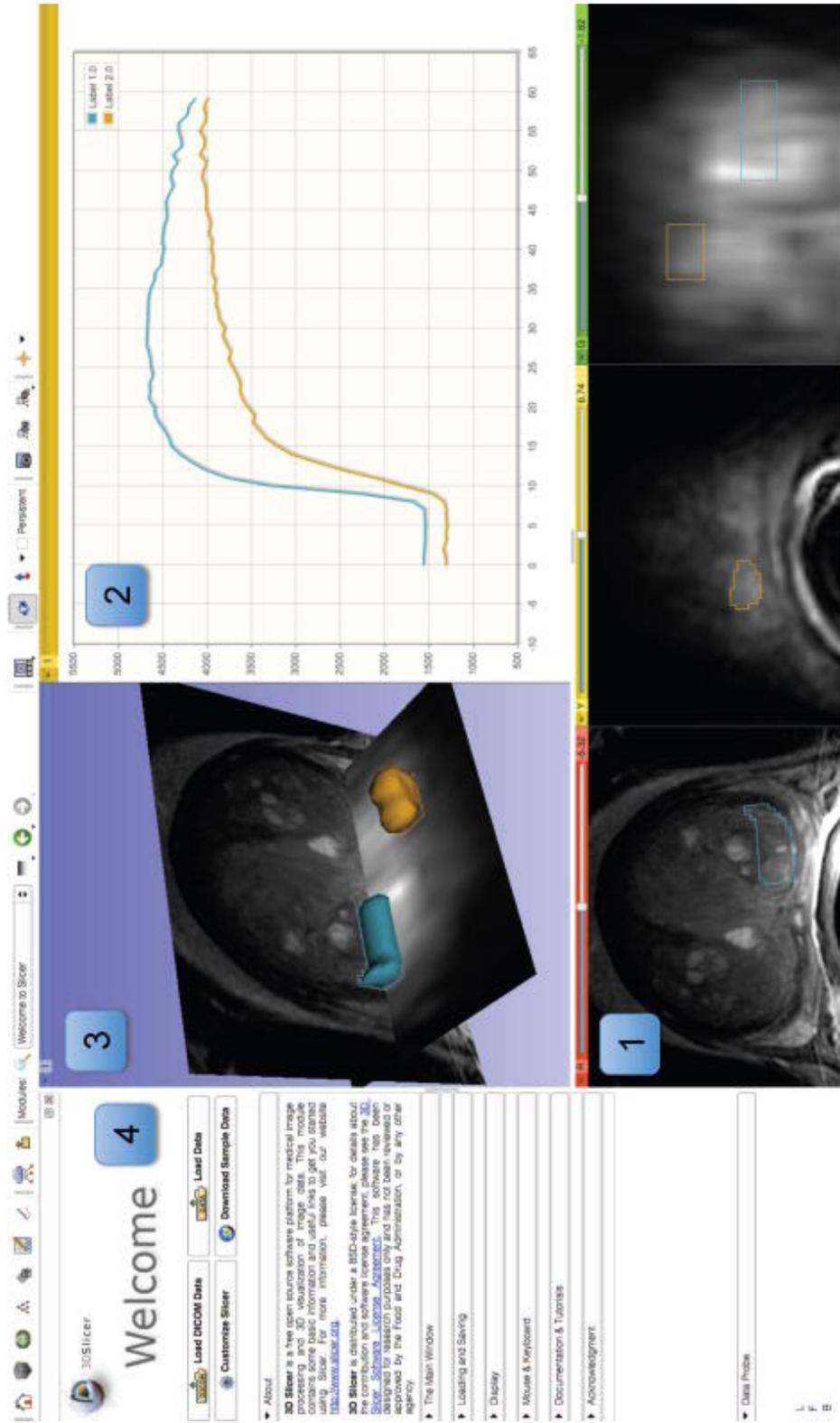


Figure 4.3: 3D Slicer: Basic layout with the welcome panel on the left side for the loading of different modules. Furthermore a Chart Viewer is displayed, which provides additional information about the prostate displayed in 3D and 2D views. The image is taken from [FBKC⁺12]

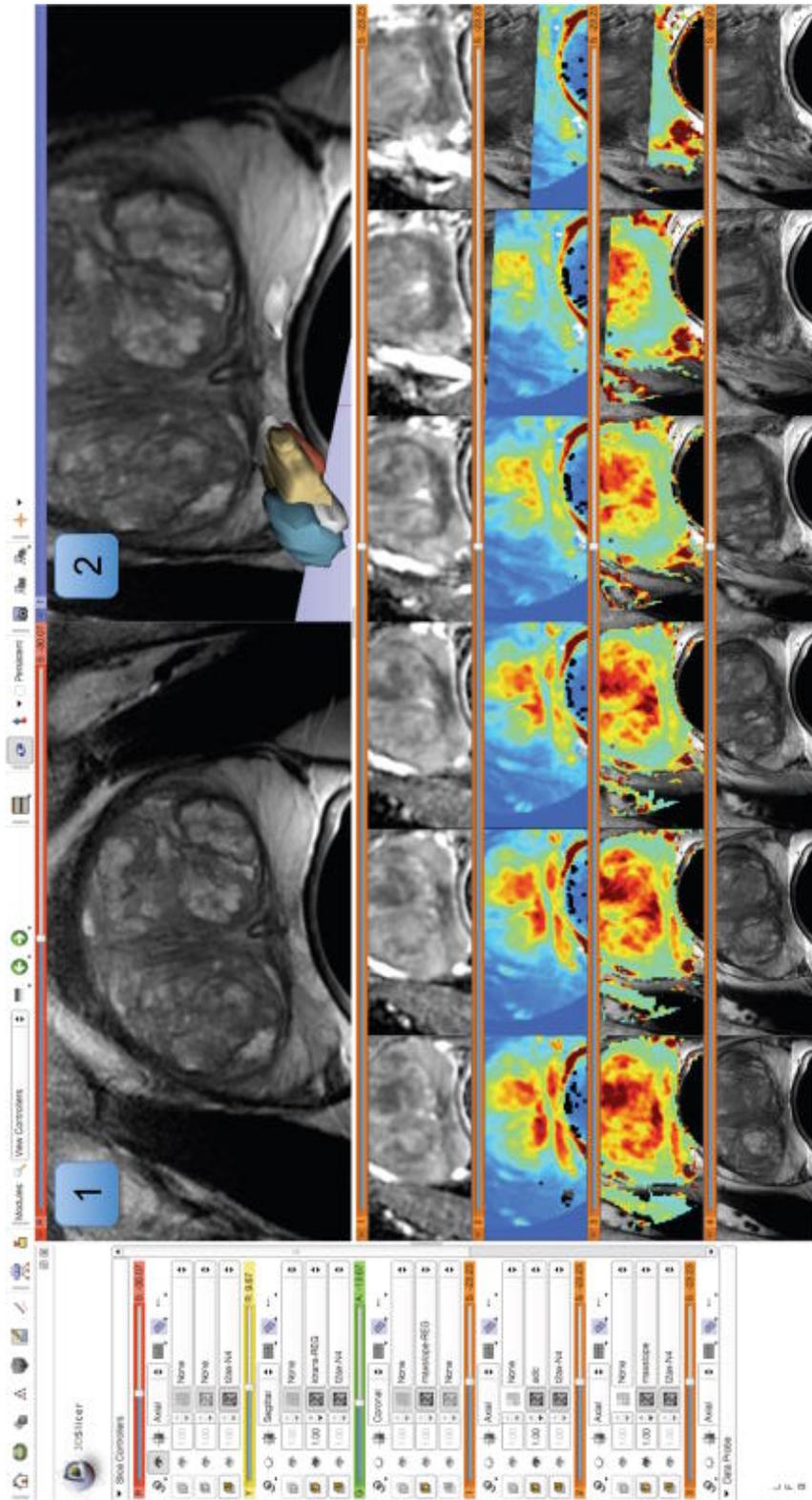


Figure 4.4: 3D Slicer: Visualization of the prostate dataset by combining different 3D renderings and 2D slice views to analyze multidimensional data. The image is taken from [FBKC⁺12]

4.2.2 Multivariate Material Data

Examples of systems that primarily analyze spatial material data are proprietary applications such as VGSTUDIO MAX from Volume Graphics [Vol] or Avizo from Thermo Fisher Scientific [The]. Both systems focus on the interactive visualization and calculation of 3D datasets, mostly from imaging techniques like CT. The interface of both applications can be seen in Figure 4.5 and Figure 4.6. Both systems present the results visually in 2D and 3D views, although the main focus in these applications is rather related to the expression of the computed numerical values.

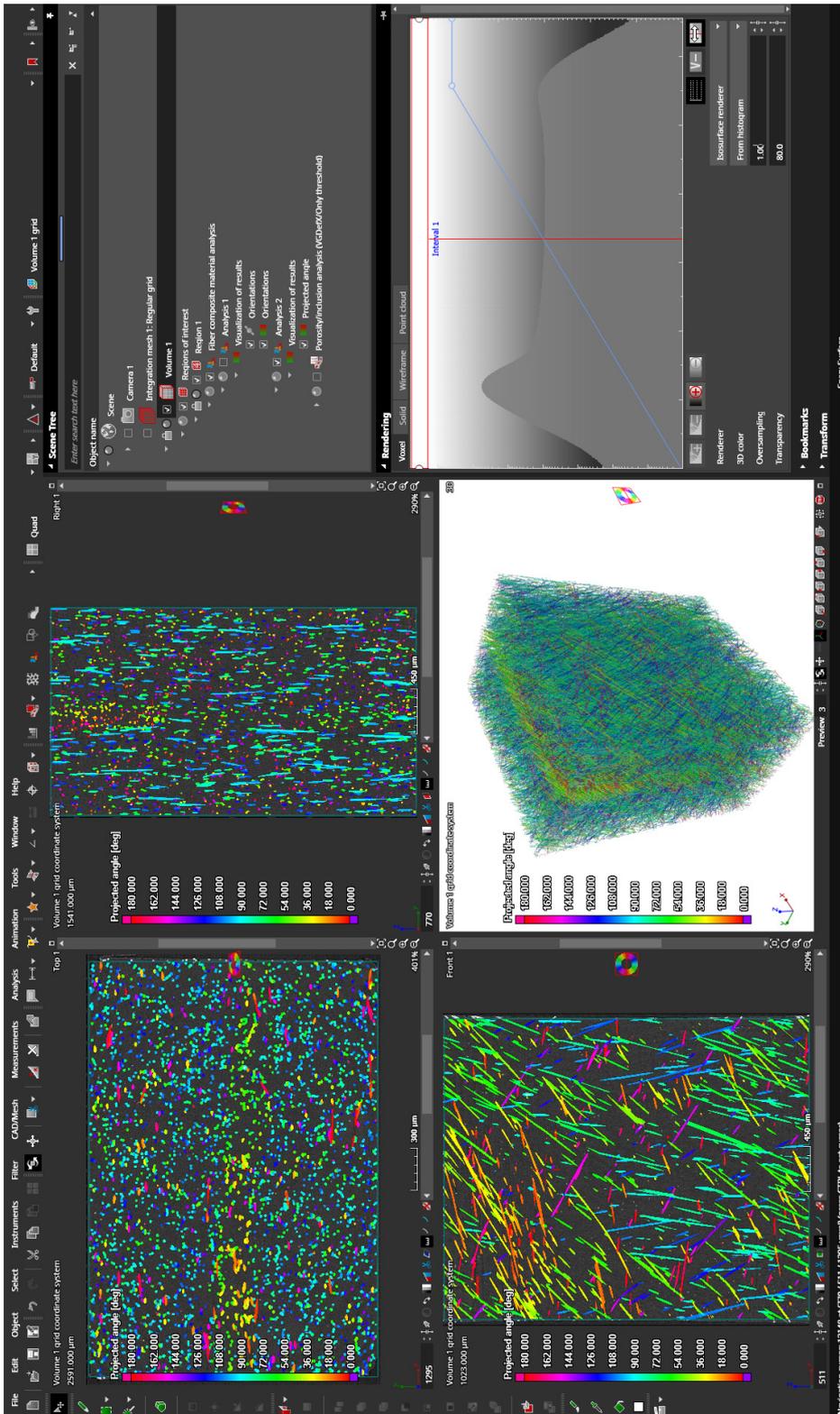


Figure 4.5: Basic structure of the VGSTUDIO MAX [Vol] graphical user interface with 2D and 3D views of the volume to explore the fiber characteristics. Here the fiber orientation is represented by projection on the front plane.

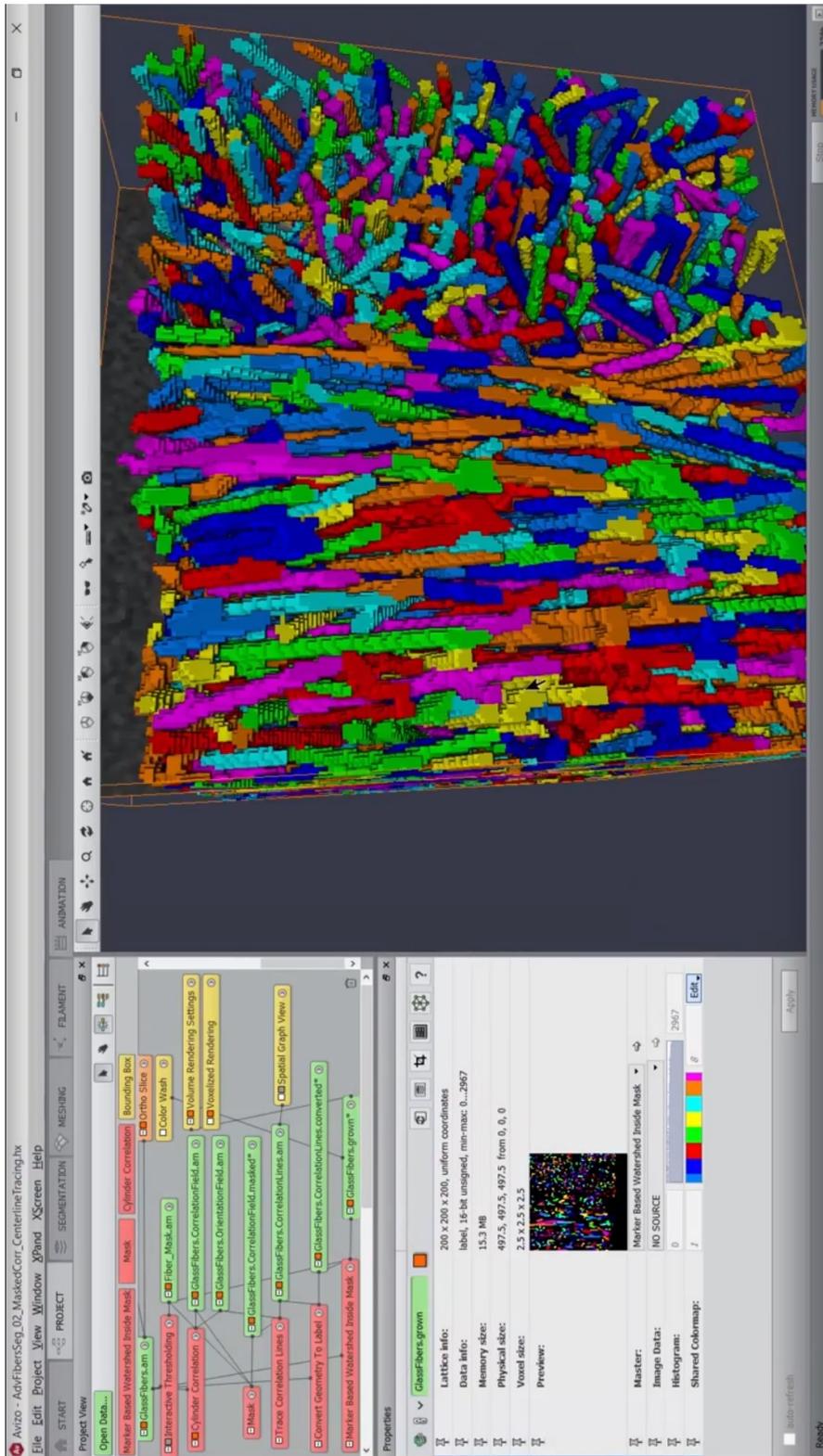


Figure 4.6: Illustration of the Avizo interface and some of its capabilities of visualizing fiber data. On the upper left part of the window the Project View is visible, which acts as node editor to link together different modules with various operations in a pipeline structure. The image is taken from [The18]

An example of an open source system based on Python is Quanfima ("Quantitative Analysis of Fibrous Materials") [SSS⁺19]. This tool allows the user the analysis of hybrid biomaterials and supports the evaluation of fiber orientation, fiber diameter, and porosity. The authors main goal was to create a plug and play package for rapid prototyping that could be applied to a wide range of data and is quickly extensible, so Python was chosen as the underlying technology. The analysis of the fibers is possible in 2D as well as 3D views and can be extended by additional statistic packages. Figure 4.7 shows 3D and 2D views of a cryogel scaffold with different encodings. The system is easy to use and expandable, but does not facilitate interactive exploration or interaction with the data. Also, without the 3D view, filtering, is only partially comprehensible due to the resulting clutter and requires high cognitive effort to understand the spatial representation.

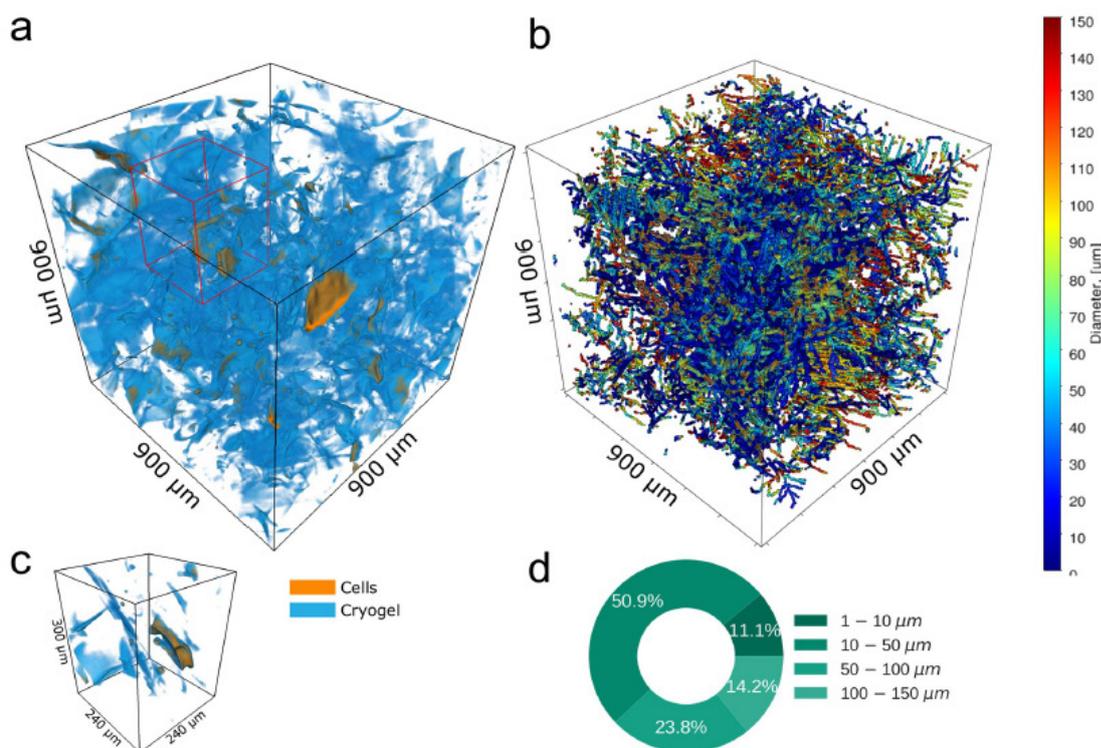


Figure 4.7: Quanfima: 3D images of a cryogel scaffold with pancreatic cells (a) and the corresponding diameter calculation (b). A detailed view of a region of interest (ROI) is selected (c) and a 2D view gives information about the scaffold wall thickness (d). The image is taken from [SSS⁺19]

Another application for the visual analysis and processing of volumetric datasets is open_iA [FWS⁺19]. Here the focus lies on the analysis of industrial CT datasets. The basic structure of the tool is written in C++ using Qt, VTK, and ITK. The framework aims to support data analysts in domain-specific tasks by offering tailored modules

that enhance the application with task specific functions. Among other functions, these modules provide the ability to determine the best scanning parameters for a given specimen [AHRG10], make visual comparisons between different volumes using Hilbert curves [WFG⁺19], visualize parameter distributions of various objects in fiber reinforced materials, and much more. The system supports the loading of various volumetric datasets in different file formats. An example for the graphical interface of `open_iA`, after loading a volumetric dataset, can be seen in Figure 4.8.

Of special interest for this thesis is the `open_iA` module `FiberScout` [WAL⁺14]. This module has the purpose to process X-ray computed tomography data of fiber-reinforced polymers in such a way that an interactive exploration and visual analysis of the properties is made possible. The tool uses a fiber characterization pipeline, in which the volume data is segmented to recognize the individual fibers and then label every voxel of the detected fibers. After that the characteristic properties of all fibers are calculated and stored in a file. After this preprocessing step the labelled data is visualized in different views. Figure 4.9 shows some of the possible views. In addition to the 3D rendered image, the `FiberScout` module adds further abstract data analysis tools. Among other views, a scatter plot matrix and a parallel coordinates plot facilitate the comparison of features against each other. The two plot types are linked, allowing the viewer the selection of specific values, which can reveal hidden relationships in the characteristics. Although this tool offers great benefits to domain experts in the data analysis, there is little support in the exploration of spatial features. For example, it is possible to create classes of characteristics with similar values, but finding features in a particular sub-region is missing. Also the interaction with a three-dimensional volume on a 2D monitor is not very intuitive and easy.

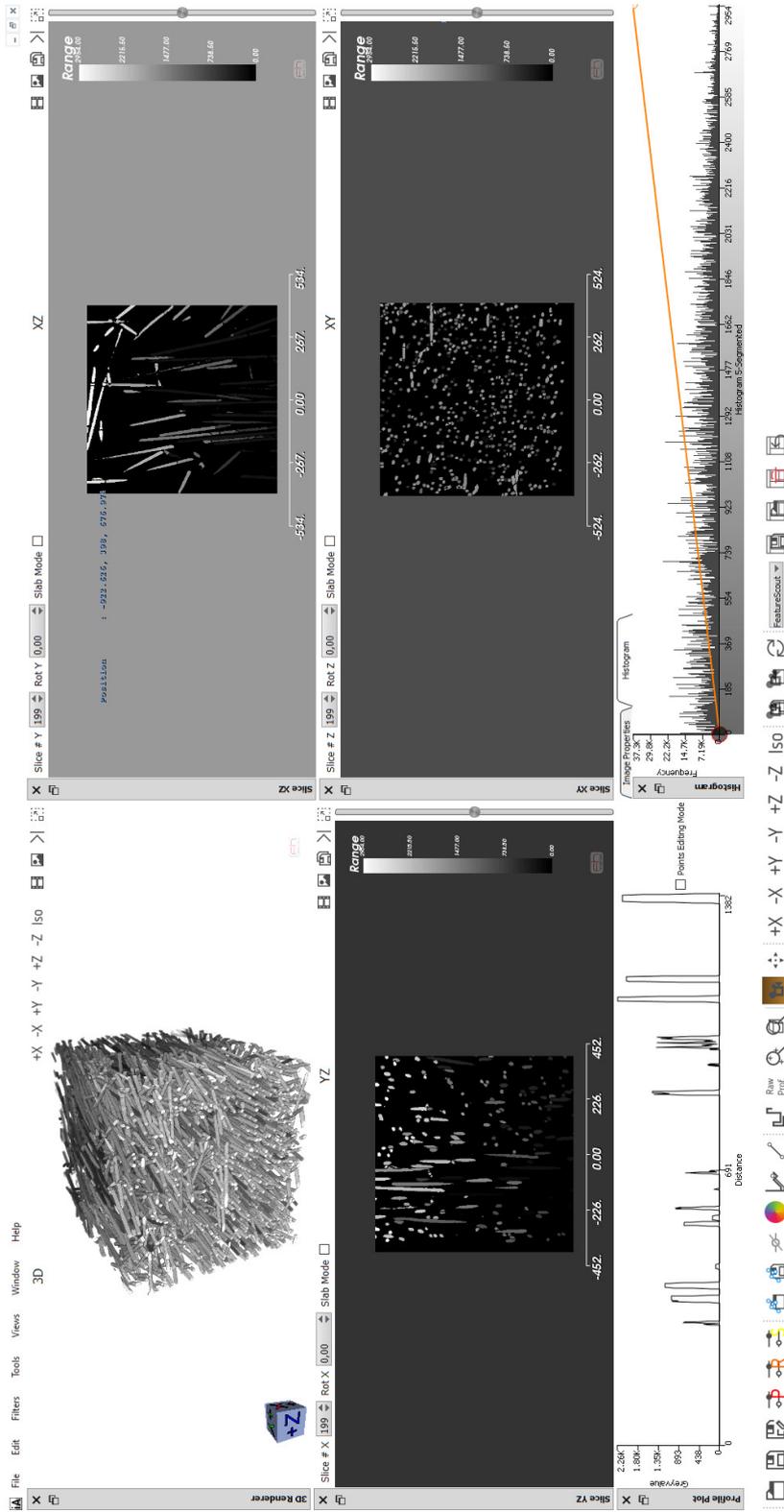


Figure 4.8: Overview of the typical layout of open_iA [FWS⁺19]. Here a volumetric fiber dataset was loaded and rendered in 3D, as well as through three slice views. Furthermore, a histogram and a profile plot for additional information is displayed. The histogram shows the intensity distribution in the whole volume and the profile plot shows the intensity along a certain line through the dataset.

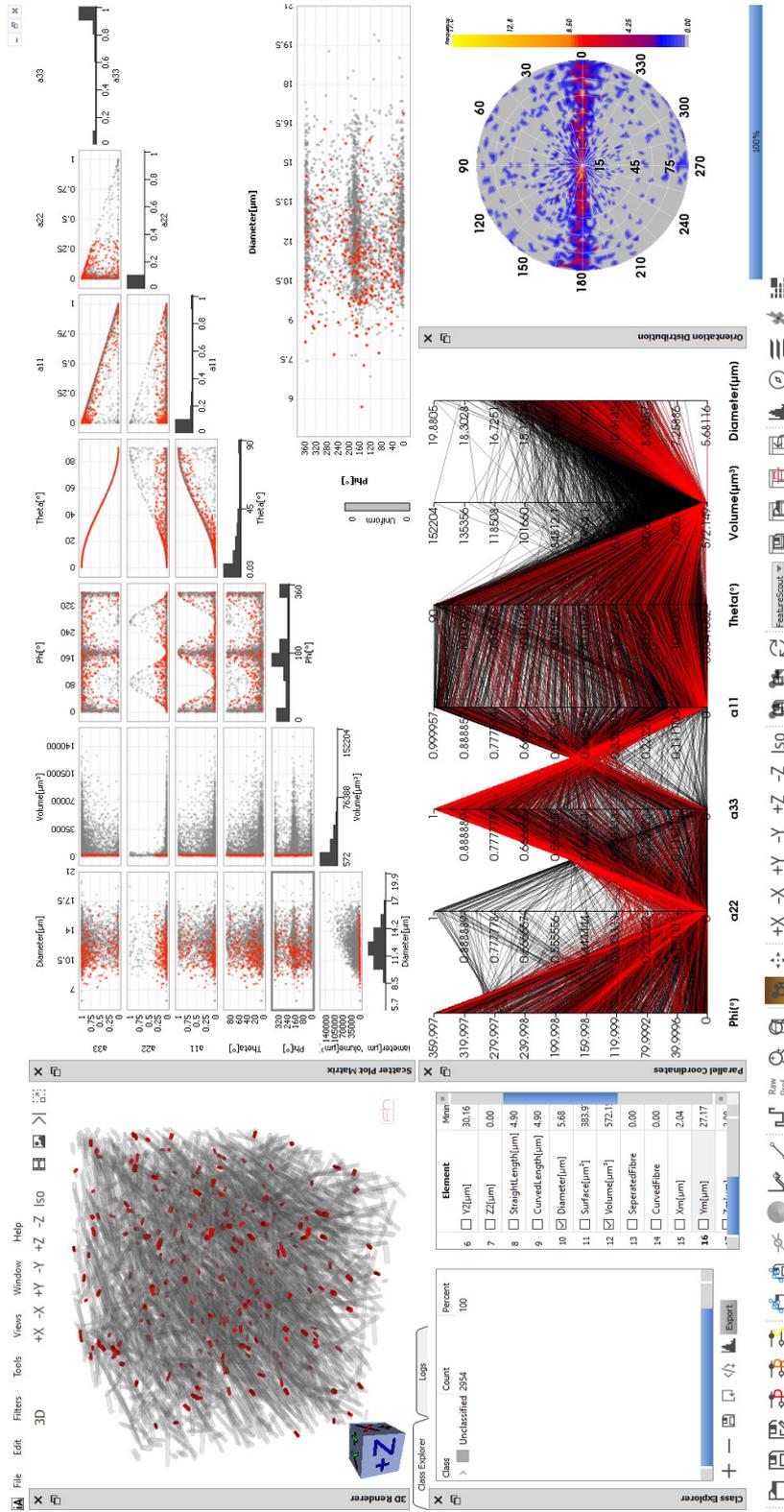


Figure 4.9: Structure of the graphical interface of the FiberScout module [WAL⁺14]. Here various 2D and 3D views are used to display the different fiber composite materials.

4.3 Immersive Analytics

Immersive Analytics addresses previously mentioned shortcomings. Since this area of research is currently in the process of defining its fields of application, in which it is most beneficial, only a few studies in the domain of material sciences have been published so far. Therefore, as described in Section 4.1, we will first present in Subsection 4.3.1 systems that represent abstract data in various forms in immersive environments. In Subsection 4.3.2 we will then show the few attempts, we have found in the literature, to visualize volume data.

4.3.1 Multivariate Data

ImAxes is a great example for the immersive visualization of multivariate abstract data by Cordeil et al. [CCD⁺17]. This work focuses on methods for data exploration that do not require traditional input methods, such as mouse and keyboard, to develop new innovative analysis techniques. The system is based on Unity [Tec] in combination with current VR HMDs. In this application, the user can load multivariate datasets, in which the attributes are displayed on single axes in the form of histograms, which can be seen in Figure 4.10. In the environment the user is given the ability to move freely and grab these axes and place them anywhere in the world. By a special grammar it is then possible to connect the axes to scatterplots and scatterplot matrices or parallel coordinates plots. This enables more natural and embodied interactions with the data. Since the work uses abstract data without inherent spatial arrangement, the type and layout of the visualizations (2D, 2.5D, and 3D) is more flexible than in traditional WIMP interfaces. On the other hand, the spatial position has less informative value than when using volumes as database. A strong engaging effect, a flat learning curve and the overall positive influence on the exploration was confirmed in a follow-up study by Batch et al. [BCC⁺19].

The Immersive Analytics Toolkit (IATK) is another application by Cordeil et al. [CCB⁺19] that extends this concept. It is a framework based on Unity, in which huge amounts of multidimensional data can be visualized and interacted with. The user has the possibility to create in an editor different information visualizations like scatterplots, lineplots, bar charts and others. The framework and some of its representations can be seen in Figure 4.11. These visualizations are encoded in the most suitable way using a grammar and the user can interact with them via brushing and linking. The system offers a variety of charts that can be displayed in VR and AR, but the settings for these non-spatial datasets must be specified on the desktop.

The authors Lee et al. [LCPD19] have added a collaborative aspect to the IATK toolkit in their system called FIESTA. The methods for creating visualizations have been adopted and combined with an environment, in which several team members can work synchronously on one dataset. In this shared environment they see their avatars and communicate through hand gestures, the currently generated representation, and voice, to share their insights. The created visualizations can be copied and moved, and respective selections are highlighted for the other users. To facilitate interaction and exploration,

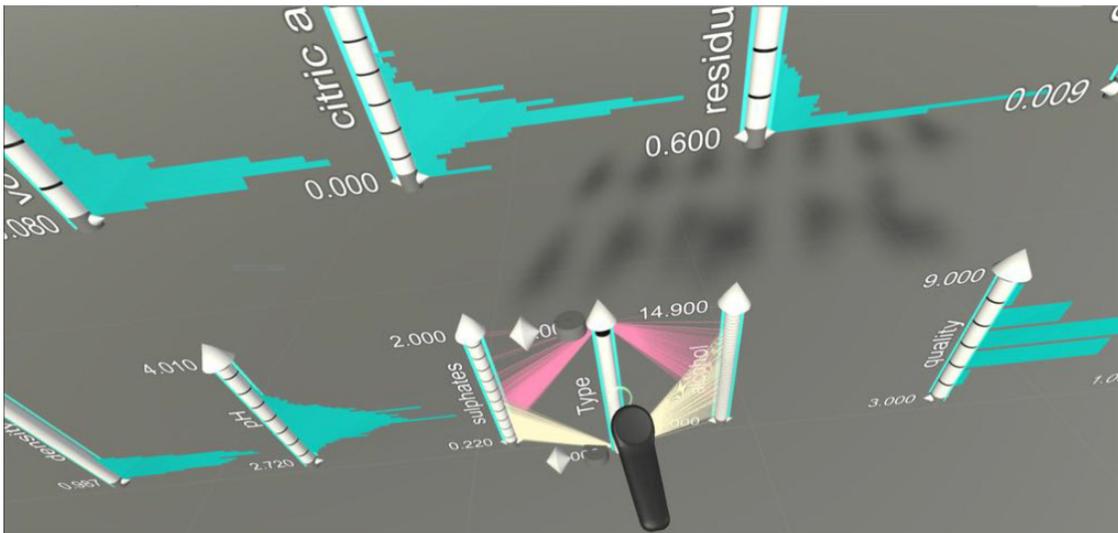


Figure 4.10: Each of the possible attributes is displayed with a single axis as a histogram in a virtual shelf layout. By combining the axes, linked views and specific charts are created. The image is taken from [CCD⁺17].

only 2D diagrams were used and displayed as billboards. The structure of the environment with the avatars of the users can be seen in Figure 4.12.

The project of Nguyen et al. [HBU⁺19] also deals with the immersive representation of complex multidimensional data in a collaborative setting. For this purpose three-dimensional Star Plots and Star Coordinates are used, where single data points as well as the whole diagram can be manipulated. However, their system does not offer any spatial data or new types of visualization techniques. An example scene from the application can be seen in Figure 4.13.

The recently developed application of Liu et al. [LPED20] focuses on the utilization of the immersive space for the positioning of visualizations. They adapt the well-known visualization idiom of small multiples for VR. This form of comparison of different datasets works very well, but suffers at a high number of representations from the limited available screen space. Due to the immersive workspace, there are several ways to arrange the layout. The paper [LPED20] compares the task effectiveness based on the selected grid structure, curvature, aspect ratio, and orientation of the individual displays. They identified that the arrangement of small multiples in a circle around the user is the least efficient layout, as it is difficult to localize a particular diagram and it is not possible to get an overview at a glance. The positive effect of a flat layout and a half-circular layout in the immersive workspace depends on the number of displayed diagrams. The flat layout is better with fewer charts as it allows the viewer to get a quick overview and requires less walking. If multiple charts in the room are needed in parallel, they identified a half-circle layout was preferred. In general, the visualizations were implemented with a

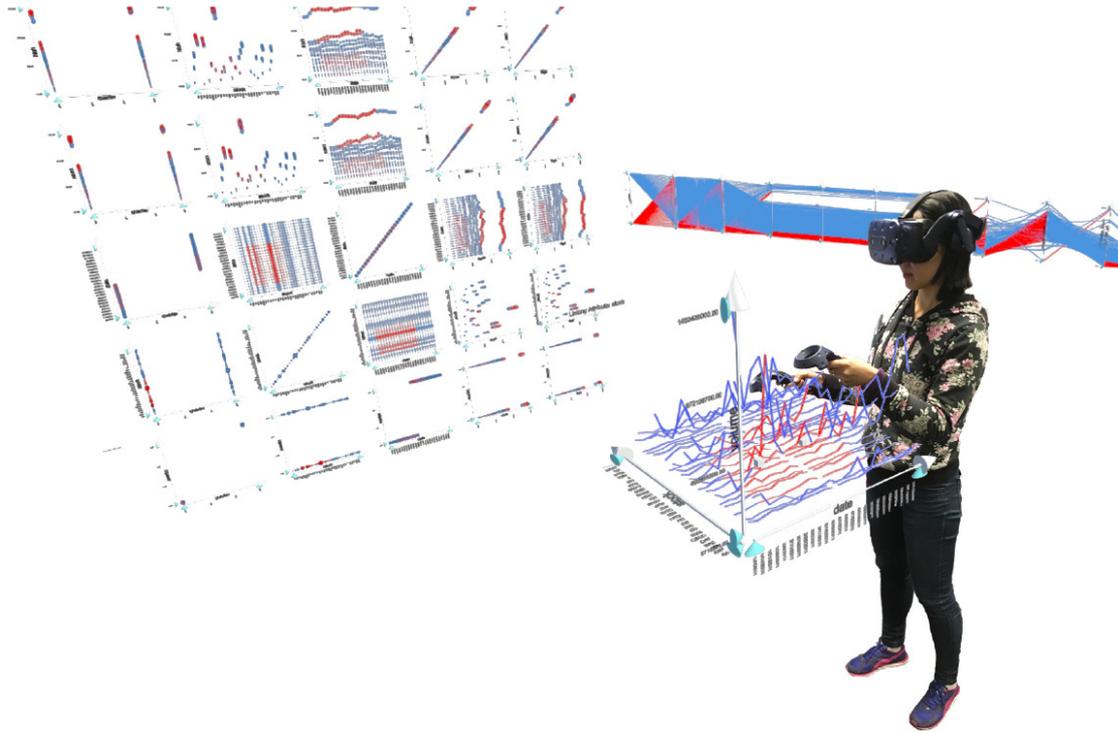


Figure 4.11: Exploration of a multidimensional dataset by a scatterplot matrix and parallel coordinates. The user can brush through the visualization and the corresponding points are highlighted in the linked representations. The image is taken from [CCB⁺19]

shelf metaphor to move all diagrams at once and rearrange individual ones, which can be seen in Figure 4.14.

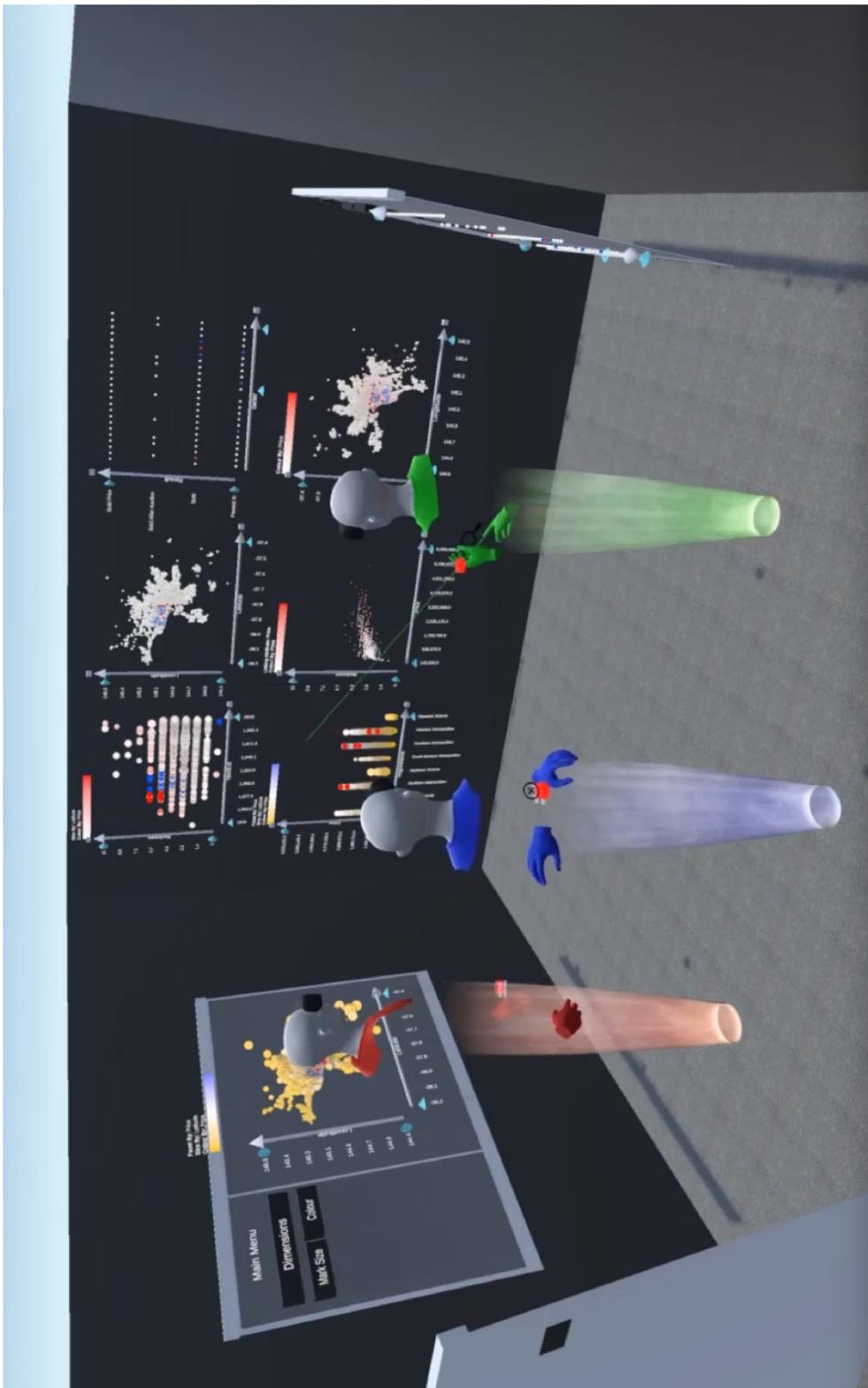
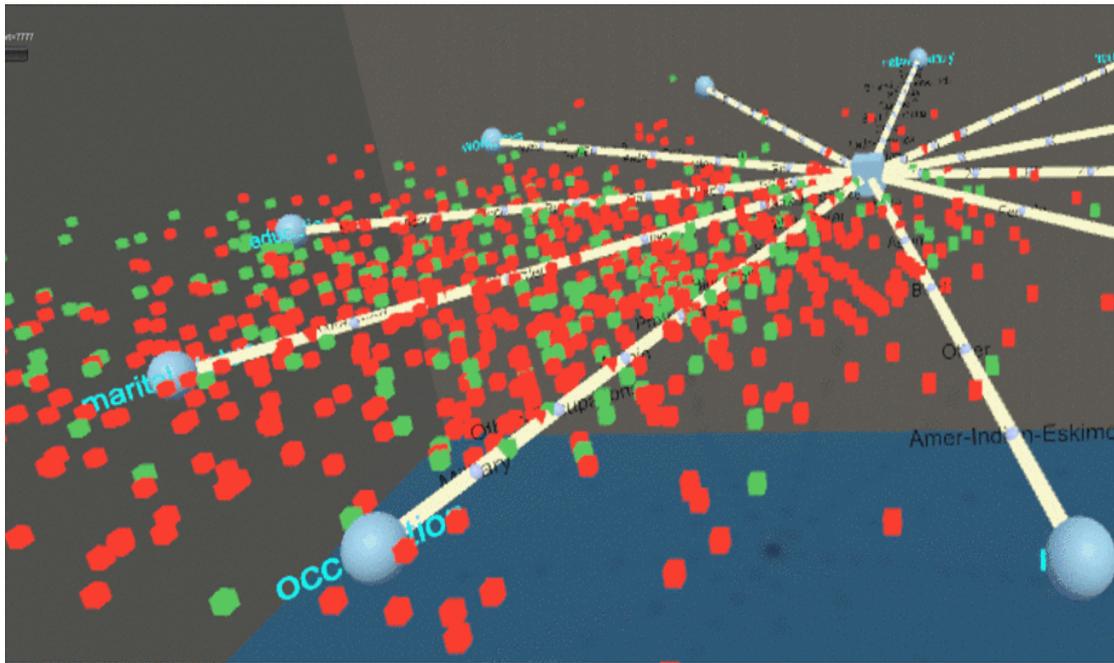
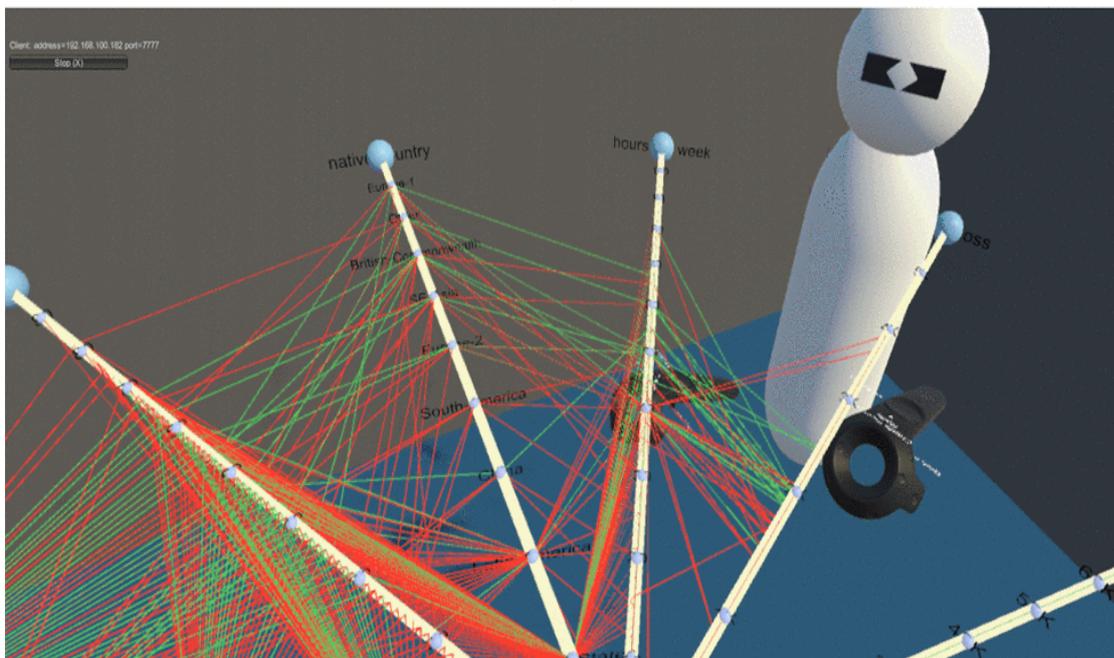


Figure 4.12: Shared environment of the exploration workspace in the FIESTA application. In the space users can see their respective avatars and discuss, copy, and share their visualizations in real-time. The image is taken from [LCPD19].



(a)



(b)

Figure 4.13: Display of the collaborative environment, in which Star Coordinates (a) and a Star Plot (b) are analyzed in a first-person view. The image is taken from [HBU⁺19].

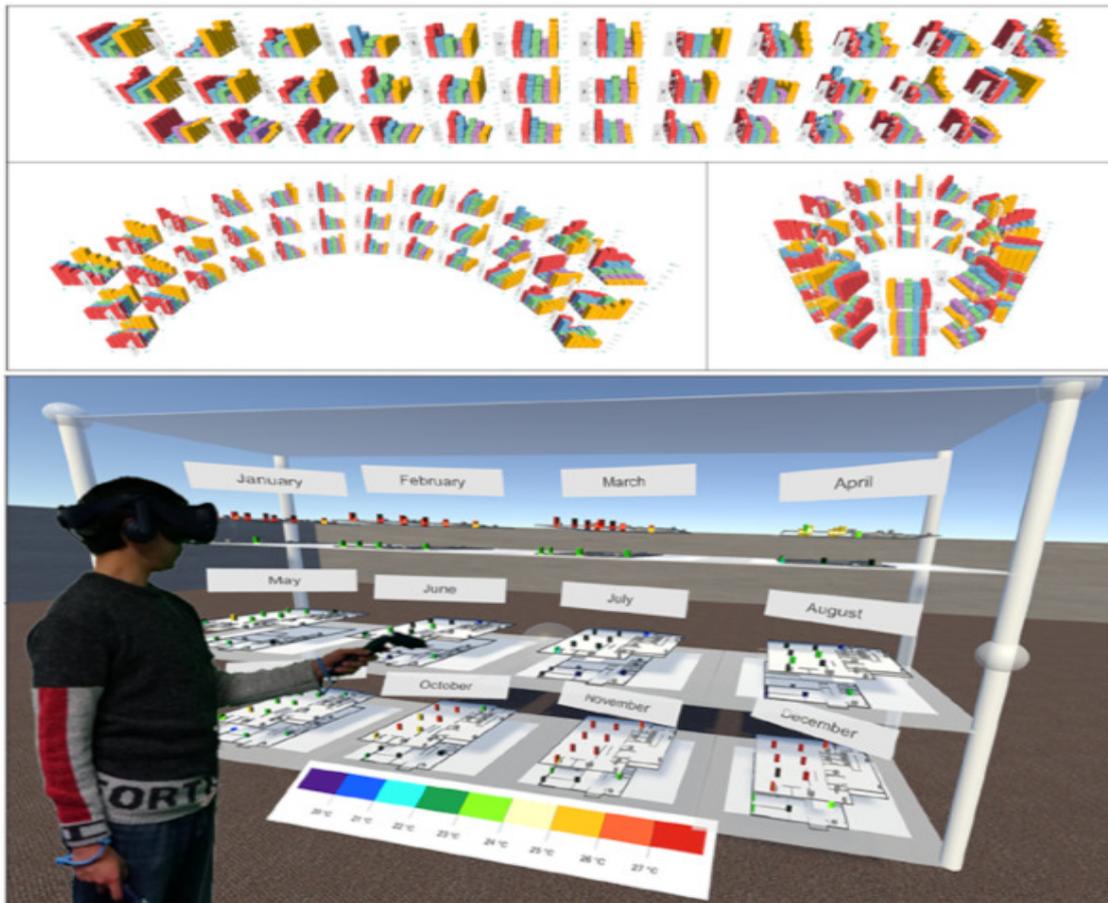


Figure 4.14: Possible arrangements of small multiples visualizations in space. The visualizations can be arranged in a shelf metaphor to manually organize charts. The image is taken from [LPED20]

4.3.2 Multivariate Volume Data

The studies of Laha et al. [LSSB12, LBS13, LBS16] focus on the visualization of volumetric data in virtual environments. Their first work investigates the effect of immersion in the analysis of CT datasets. They tested specific tasks in a CAVE environment and found positive effects concerning exploration. Different tasks performed differently, but especially the spatial search for certain features benefited most from immersion. A subsequent study extended the setting by a head-mounted display. They examined the same tasks and found a positive effect of head tracking. However, the drawbacks were the slightly restricted freedom of movement and the weight of the HMD during exploration. Another project is concerned with the most effective form of interaction with volume data. The Volume Cracker is a form of interaction, in which a volume can be broken up by natural gestures. The results generally show an advantage when using 3D interactions to manipulate volumes.

An early publication by Jackson et al. [Kee13] also indicates positive effects of 3D interaction for the exploration of fiber structures. They use a cylindrical, tangible object to filter fibers in a volume. Only the fibers in the volume that have the same orientation as the tangible object are shown on a 3D display. This natural form of interaction can make visualization techniques more effective and engaging. An image of the general setup and the rendered fibers is shown in Figure 4.15.

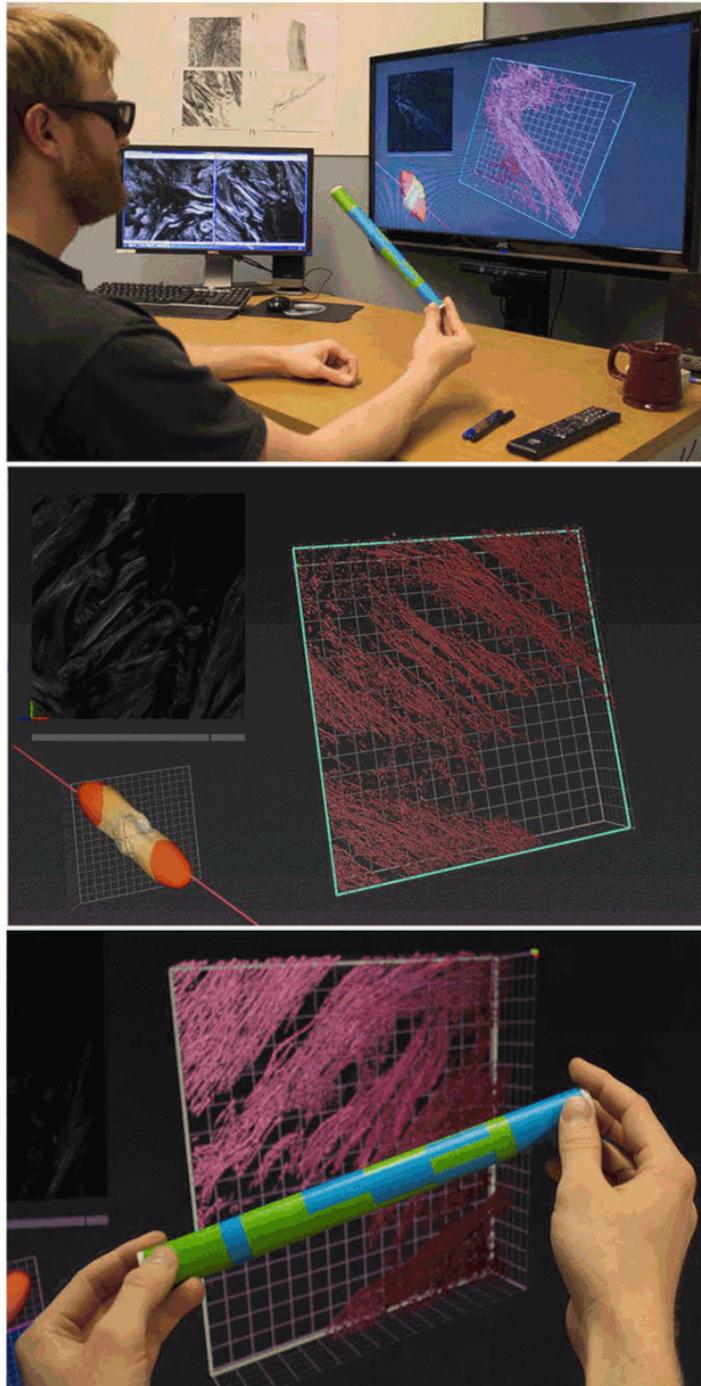


Figure 4.15: Fiber exploration in front of a 3D display. The user can filter for fibers that have the same orientation as the tangible object. A depth camera registers the pattern on the object and is used to control the 2D and 3D views of the volume. The image is taken from [Kee13]

A project focusing on the field of material science has been done by Drouhard et al. [DSH⁺15]. They aim to simplify the steep learning curve of current applications for visualizing complex, high-dimensional datasets using VR. They use the Oculus Rift with Unity to visualize crystal structures of molecules with up to 12,000 atoms. They found that a better overview of the volume is achieved, as well as user-friendliness and scalability for large data are of great benefit.

A very promising example for the visualization of complex 3D trajectories, including fibers of the brain, is presented by Hurter et al. [HRD⁺19]. Complex and large datasets from aerospace and medicine are used to visualize and interact with in virtual reality, which can be seen in Figure 4.16. They show that the exploration of the inherently spatial data, which is extended by abstract information, can be further improved by special 3D interactions. In their work they attempt to avoid 2D GUI components and multiple mode changes. A single main view is used to ensure an intense immersion. Different views of the visualization or mappings are made possible by physically moving on a virtual grid. When moving, an interpolation between the views is performed. In order to enable a seated exploration, the controllers can also be used for navigation. By aiming a ray from the controller at a trajectory and pressing a button, the trajectory can be selected. Through qualitative user feedback they discovered that by being able to change one's perspective, the immersive setting helps to perceive patterns that are otherwise difficult to detect.

The last research paper presented here was only published very recently. The work of Wang et al. [WZYW20] deals with immersive volume visualization techniques. Their main focus was on fluid interaction via gestures to manipulate different optical properties of a volume. The goal is to create a What You See is What You Get (WYSIWYG) pipeline using a VR HMD and Leap Motion to track the user's hands. The ability to use simple wipe or point and drag gestures to switch between slices, or to change the contrast and saturation has improved exploration and enhanced the user's visual cognitive abilities.

As can be seen from the applications shown, there are several multidimensional data visualization systems, but they are aimed at 2D representations or have not tried to visualize volume data in their IA approaches. A strong motivation of this thesis is to emphasize the physical component of the inherent spatial data. The users should have the possibility to perceive volumes physically as accurately as possible and not as "flattened" 3D representations. As result, viewers can rely on their natural spatial perception, limiting their cognitive workload. The focus should be on augmenting the spatial representation with the abstract data and enabling a more engaged exploration compared to current Visual Analytics approaches. To our knowledge, this work is the first research in the field of immersive visualization and interaction of multidimensional volumetric fiber data.

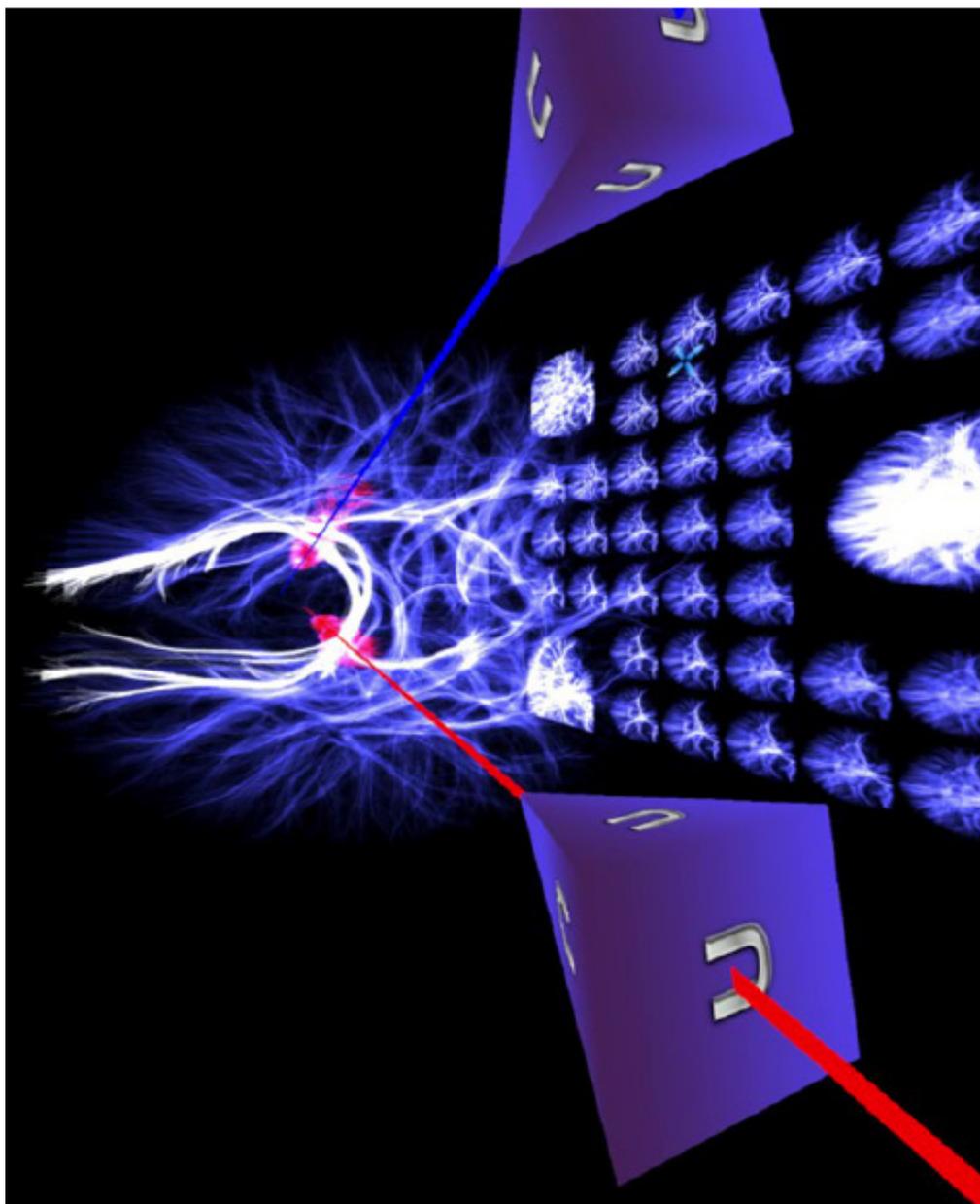


Figure 4.16: Interaction with a brain dataset, in which the fibers were extracted. It is possible to select specific fiber bundles or interpolate between simplified views. The image is taken from [HRD⁺19]

Methodology

This chapter deals with the structure of our Immersive Analytics Framework. In Section 5.1, we first discuss the approach towards designing the application on the basis of the data, the tasks, and the idioms used. We will describe the key considerations needed for an interactive visual analysis in immersive environments. After the introduction, the basic structure of the virtual world is covered in Section 5.2, followed by an explanation of the chosen spatial data structure for the volume in Section 5.3.

In the following sections the developed visualizations and interaction techniques are explained in detail. The respective methods are discussed using the Visual Information Seeking Mantra of Shneiderman [Ben96] and the Visual Analytics Mantra of Keim et al. [SBM08, pp. 76-90]. The former follows the procedure *overview first, zoom and filter, then details on demand* and the latter extends it with *analysis first - show the important - zoom, filter and analyse further - details on demand*. We will organize the methods according to their function to provide overview, enable filtering, and offer detailed information to support the exploration.

5.1 Design Considerations

For the development of immersive analytical research and applications, a design framework is needed. IA research can only be efficiently designed and evaluated by methodically structuring the design decisions. In this thesis we use the *Where-What-Who-Why-How* framework, which is tailored to Immersive Analytics. This framework presented by Marriott et al. [Mar18, Chapter 9] is a modification of Brehmer and Munzner's [BM13, Mun14] *What-Why-How* data visualization framework.

- **Where** – summarizes what type of device with what interaction possibilities are available. The question Where also determines what this virtual world looks like

and whether it contains information about the physical world. The corresponding design decisions are explained in more detail in Section 5.2.

- **What** – is concerned with questions about the data type and its attributes. In this thesis, multidimensional attributes in tabular form with spatial reference are processed. The quantitative data is stored in a .csv file and is statically available. The attributes are sequentially ordered by the detected fibers and consist of about 20 or more features.
- **Who** – addresses the users that work with the system. In this thesis the main target group are single users, who are engaged in the exploration of fiber reinforced polymers. Domain experts should be supported by additional insights, but also novices should benefit from the application.
- **Why** – attempts to define the tasks and their targets. In this project the high-level user tasks are discover and enjoy. In discovery, the goal is to find new hypotheses regarding fiber characteristics or to verify or falsify existing ones. Enjoyment is a further goal, since the immersive environment is intended to raise the interest of the user even without prior hypotheses, resulting in a longer use of the application due to the engaging effect. Motivated by the users enjoyment they gain insights from their own curiosity. The search is driven by exploration in order to discover certain fiber characteristics at specific locations in the volume. The produce tasks, classified by Marriott as medium-level tasks, arise in our case through the user's exploration and take the discovery even further. They can lead to the calculation of certain distributions or neighborhood relations, which is described in detail in the presented techniques of our framework. Finally, the targets are the individual features of the fibers in the volume. Their distributions, extremes, as well as their spatial shape are of interest to the expert.
- **How** – focuses on the design of the visualization idiom. In Immersive Analytics applications the number of possible representations is increased compared to standard 2D desktop visualization techniques. The encoding is still based on colors, sizes, and shapes, but is extended by the spatial component. The form of manipulation in this thesis will also be characterized by immersive components such as the direction of gaze and embodied interactions. Furthermore, the type of faceting is characterized by the positioning of the representations in space and adaptive to the positioning of the user. The type of rendering, and as result, the degree of fidelity, also needs to be considered in IA, which is why a cylindrical representation of the fibers was chosen. In order to reduce the data in our approach, filtering techniques and aggregations are used. All design criteria employed in this thesis are explained in the following sections during the design of the respective visualization technique.

Additional considerations for our framework that enhance immersion and exploration are:

1. **Allow for Scalability** – To enable exploration of different volumes, the system must be able to display both small and large datasets. Therefore, the environment and the visualization methods must be chosen carefully to allow for smooth and interactive use and rendering.
2. **Avoiding control components** – Standard desktop applications are based on WIMP techniques, which do not necessarily work very efficiently in three-dimensional workspaces. Our tool does not use 2D GUI components like menus and aims more at natural interaction via controller actions.
3. **Avoidance of unjustified 2D representations** – Since both the advantages and disadvantages of 2D representations in immersive environments are not fully understood, 3D visualizations are preferred in this system to take full advantage of the system’s possibilities.
4. **Versatility** – For the discovery of certain fiber characteristics by exploration (where both the target and the position are unknown) expressive techniques are important. It is essential to offer the user different visualization types to highlight different aspects of the dataset.
5. **Making manual mode switching unnecessary** – In order to increase immersion and the feeling of presence, frequent switching between different modes is avoided to allow natural interactions that are adapted to specific situations.
6. **Facilitate office work** – Although the focus is on embodied interaction, the typical working environment of the user is also relevant. For this reason, the navigation should also be easy to use in a seated position by using the controllers.
7. **Ready-to-use tools** – To enable efficient exploration, the tools must be available quickly. In this thesis we use an intuitive interaction and visualization technique called Model in Miniature (MiM) to have one’s tools quickly in place.
8. **Limit to the essentials** – To keep the complexity low and to increase the immersion with the volume only one primary view is used. Multiple representations are not simultaneously placed in the world and the user interacts primarily with the volume and the Model in Miniature.

5.2 Immersive Workspace

Some of the design considerations are motivated by the objective of viewing the immersive environment as the analyst’s workplace. The interactions should feel naturally and the tools should support the workflow intuitively.

The start environment is a large virtual space with the volume prominently in the center. The viewer is not distracted by other aspects at the beginning and is focused on the exploration of the volume. This also provides a complete overview of the loaded data.

The individual fibers of the fiber dataset are rendered as cylinders with respective lengths and diameters. This has the purpose of better finding certain patterns than in cluttered voxel representations, and also reduces the GPU power required to ensure a smooth exploration. The background of the environment is depicted with a gradient from black to white. The choice of background also influences the exploration. During the development of the project it was found that a pure white environment is too bright and therefore disturbing. Prolonged use in this bright environment reduces the users comfort during analysis and affects their enjoyment. Pure black environments caused an oppressive feeling among users. Both forms of environment without a horizon left the user with the feeling of working while floating. A background with a texture that is too detailed is also irritating because the limited resolution of the VR device allows the user to see the surroundings, but only blurred. Therefore a gradient was used, which fades at the approximate horizon from black to white. This also has the advantage that no color is used, which could affect the later visualization techniques. The resulting immersive workspace of the application can be seen in Figure 5.1.

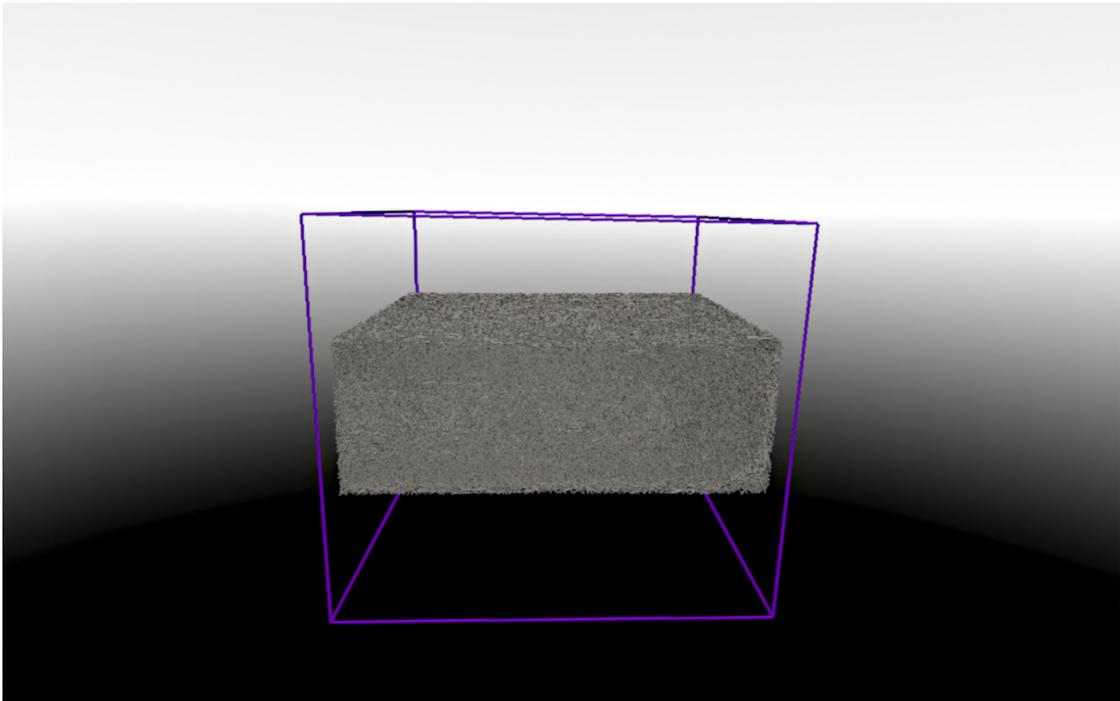


Figure 5.1: Virtual environment at the beginning of the exploration. In the immersive workspace, only the fiber volume is visible with a background whose gray values change gradually.

The environment can be navigated through embodied interaction like walking around the volume. Even views from arbitrary viewing angles are possible thanks to head tracking. Since many experts use the application in their daily work in the office, additional navigation techniques must be available. To enable a seated navigation, controller inputs

are employed. The used actions are based on real metaphors like grabbing and pulling a rope. Thereby both arms are reaching forward and move while pressing a key, which translates the world. To zoom in on the world, the two controllers are moved together or apart from each other, which shrinks or enlarges the volume. The use of translation and zooming allows the user to change position even while seated.

5.3 Spatial Octree

As partition of the volume an octree structure has been chosen. The octree data structure divides a three-dimensional space in the form of a tree into eight children, i.e., regions. These regions can then each be recursively further divided into eight children. The recursive subdivision creates different octree levels L and is performed as long as at least one object, e.g., vertex is located in this region. A complete octree, as shown in the illustration, consists of $N_L = 8^i - 1$ leaf nodes in the respective level $i = 1, 2, \dots, L$. The total number of regions can be calculated by using Equation 5.1.

$$N_{Total} = \sum_{i=1}^L 8^{(i-1)=\frac{8^L-1}{7}} \quad (5.1)$$

In our application the fiber is assumed to be a straight line defined by the fiber start and end point. The octree structure does not know the intermediate points of the line, formed by the fiber. As result, the subdivision is made as long as a fiber start or end point, saved in the .csv file, is located within a region. Each octree level is stored as a separate data structure to ensure a quick calculation of the numerous fibers. The different octree levels are used to divide the volume into quadratic regions of equal size, which define a three-dimensional area in which the later calculations will be performed. An illustration of this subdivision can be seen in Figure 5.2. Each octree level has a defined number of regions on which the later metrics can be applied.

The start and end points of the fibers from the .csv file are used for the subdivision. By using the start and end points, a fiber is assigned to a maximum of 2 regions. This would result in a loss of information for regions through which fibers pass but have neither a start nor an end point inside. To get an exact representation of the fiber distribution in the regions, the fiber coverage has to be calculated. Each fiber in each individual octree level is considered and for each region it is calculated how much of the fiber is inside a region. This makes it possible to determine for each region, which fibers are in it and at which percentage. An intersection test is made with the line formed by the start and end point of the fiber. The path of the fiber is checked for intersections with the region's borders. If a fiber intersects one or more region surfaces the length between the intersections is calculated and compared to the total length of the fiber. The 2D approach is depicted in Figure 5.3. Step 0 is the initial position of the fiber with its entire length L between start (S) and end point (E). The purple borders are the bounding

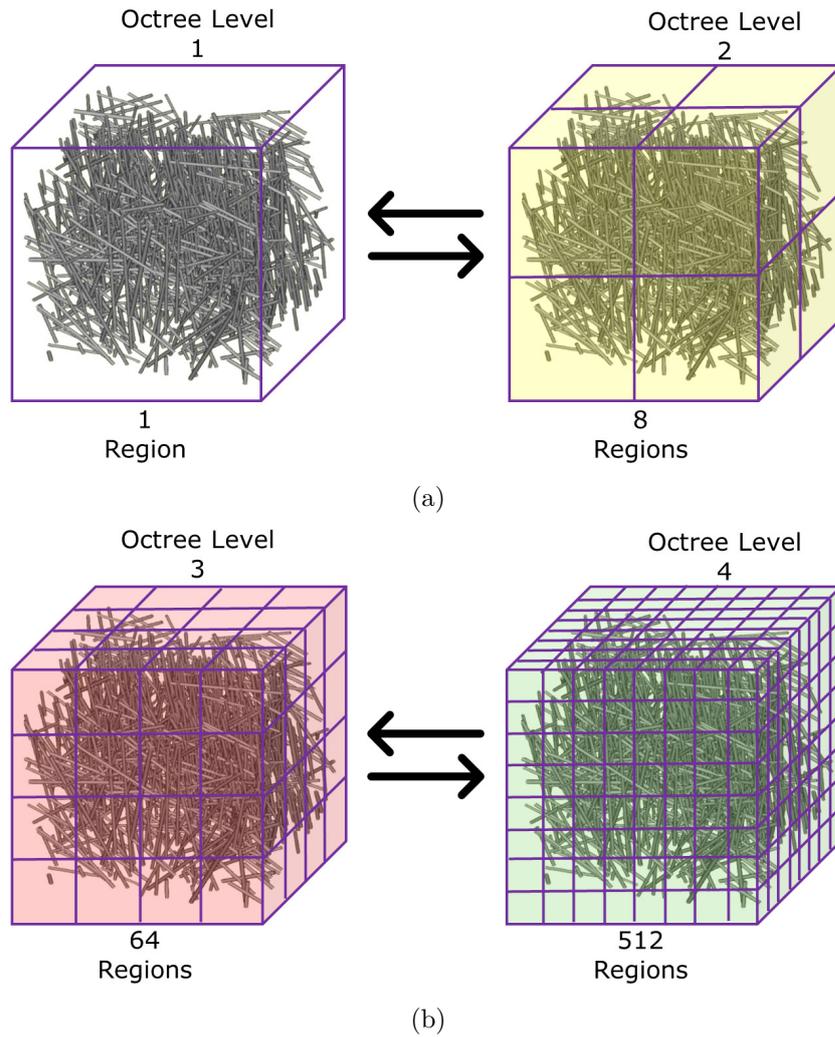


Figure 5.2: Representation of the octree structure in different levels. Level one (a) is shown on the far left and is the original volume with a bounding box around it. Level 2 (a) in yellow divides this box into eight equally sized cubes. Level three (b) in red consists of 64 cubes and level four (b) contains 512 subvolumes.

box of a region. In Step 1, the first intersection of a fiber with the surface of a region is detected. The length L_1 between S and the intersection point is calculated and divided by the total length to determine the coverage in percent. Afterwards in Step 2 the path through a region is recognized, in which neither S nor E is present. Therefore the length L_2 between two intersection points is calculated and again the coverage is saved. Finally, in Step 3, the last intersection point and thus the length between E and this intersection point is calculated. Then this process is repeated for the next fiber.

The fiber coverage is calculated for each individual octree level to be able to use the trees

separately. After these calculations, for each fiber the coverage for all regions is stored. So if a fiber is contained entirely in a region, its coverage for that region would be 100 percent. This enables to determine the contribution of every fiber for each region, which is important for later calculations.

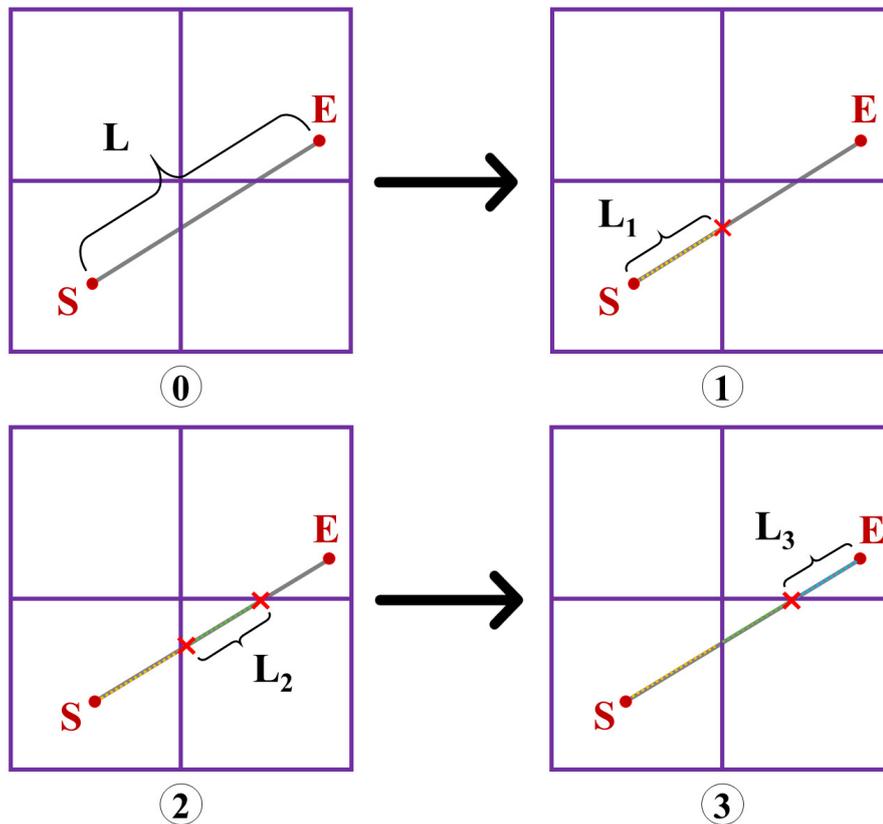


Figure 5.3: 2D Illustration of the fiber intersection test, which is performed for every individual octree level in three dimensions. From step 0 to 3, the line between the fiber start (S) and end point (E) is checked for intersections with the bounding box of the regions marked in violet. The length (L_i) between the resulting intersections is calculated and compared to the total length of the fiber (L).

This coverage is also used when displaying octree regions in the Model in Miniature and the volume. Therefore it is checked before rendering the regions if there is any fiber coverage inside. If not, the region will not be rendered. So the visualizations are not cluttered with empty regions and performance is optimized. When changing to a higher octree level, the same process is applied. The region is split into finer regions and areas, that become empty, are excluded from rendering. For the later calculations this implies that a region without fibers has the coverage of zero percent for all fibers in the volume.

5.4 Model in Miniature

The Model in Miniature (MiM) is one of the most important interaction and visualization techniques in this thesis. It is an abstract representation of the displayed volume. The structure of the spatial octree, which divides the volume, is used to create the MiM. Each region in the volume is represented by an equilateral cube in the MiM. Since the MiM is intended to provide a quick overview of the volume, the MiM's cubes are scaled down to create a miniaturized abstract copy of the volume. The process of scaling down a component of the environment and using it for interaction is derived from the well known technique World in Miniature (WIM).

5.4.1 World in Miniature

To explain the relevance and purpose behind the MiM, the underlying idea of the World in Miniature is explained in more detail. The basic technique was developed around 1995 and is used for object selection and object manipulation [Jer15, Chapter 28] [CML⁺12, WHB06, NMT⁺19, BJ19]. Since its development, this technique has been used successfully in numerous applications in virtual worlds. WIM is often defined as indirect proxy technique [Jer15, Chapter 28][MLK⁺17]. The goal is to give the user a proxy object related to a remote object. Any interactions of the proxy will be applied to the remote object instead. This exocentric miniature representation can have different designs - as a viewbox that shows a part of the environment as a real-time copy, as a 3D map in which the own avatar or objects can be repositioned or finally as a hand-held proxy, the so-called voodoo doll technique. The WIM is often an exact replication of the virtual environment and as miniature handheld model displayed to the viewer. WIMs therefore offer a very good overview and situation awareness, making it easier to manipulate large or distant objects. However, when applying transformations in the global coordinate system of the virtual world, e.g., for navigation, the viewer may get confused, because of the lack of directional compliance with the WIM. The disadvantage of the WIM results in the loss of orientation, because the user rotates the WIM and thereby the whole world. To counteract the user's confusion, the orientation of the WIM should be directly coupled with the orientation of the world.

5.4.2 Overview Exploration

In our approach we introduce a novel way of utilizing the WIM technique. We designed a proxy for the fiber volume to get an overview of the volume and interact with it. Instead of creating a copy of the whole virtual world, we developed an abstract miniature model of the volume. Our proxy, i.e., miniature model combines manipulation of the remote object, i.e., fiber volume with an information visualization of fiber characteristics. The MiM acts as hand-held visualization and 3D user interaction technique to facilitate the exploration of the large fiber volume and is called for that reason Model in Miniature. To create the abstract model an action on the controller is performed and the MiM hovers over the user's left controller. The model follows the movements of the controller, allowing

the user to take a closer look at the MiM and have it ready to use. Figure 5.4 shows the MiM with the fiber dataset in the VR environment. If the MiM occludes important information in the environment, it is possible to hide the abstract representation. To avoid orientation problems, the orientation of the MiM is directly linked to the fiber volume. As a result, the viewer is not disoriented, as the MiM is an absolute reference to the volume. This allows the user to determine the orientation of the volume even when it is not in the user's field of view. This is useful when the user enlarges the volume during exploration and is immersed in it, allowing them to determine their position and orientation. The MiM not only provides an overview of the current partitioning of the volume, but also enables the visualization of abstract data.

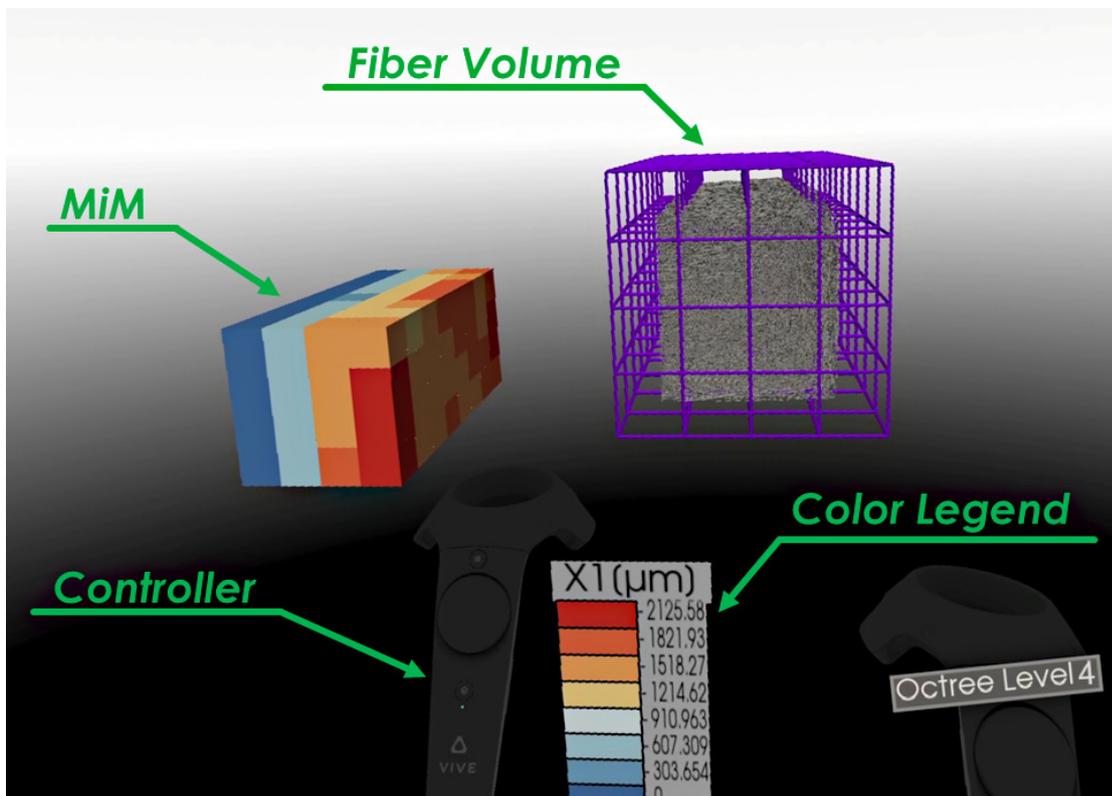


Figure 5.4: The MiM represented as colored 3D heatmap in the virtual environment. In the center the volume is shown with the same octree division as the MiM. The annotations in green were included as a description and are not shown in the application.

Heatmap

The MiM is a scaled-down depiction of the volume represented by three-dimensional cubes. To facilitate the exploration of the fiber volume, these cubes are color-coded to provide information about the multidimensional properties of the fibers. After subdividing the fiber volume through the octree into uniform regions and calculating the percentage of

fiber coverage in each region, the resulting data can be used to compute the average value of the fibers' characteristic at a specific region. With the spatial position of the cubes, which reflect the regions of the volume, and the color-coding of the cubes, the MiM becomes a 3D heatmap. This 3D heatmap shows the distribution of a fiber characteristic, computed for each region in the volume, depicted by the cubes in the MiM. By extending the MiM to a 3D heatmap it is now possible to support the user in the exploration of the large fiber volume. The color encoding of the cubes, which is explained in more detail below, helps the user to locate interesting areas and patterns and facilitates an initial hypothesis generation about the dataset. The MiM assists the user by guiding the investigation with an overview of relevant regions.

The scalar of a region, which is later mapped to a color, is calculated as weighted average of the regions fiber's characteristic. The percentage of coverage of each fiber in the respective region is used as weight. This means that if, e.g., only 20 percent of a long fiber is located in the region, its characteristic is only considered according to this percentage in the calculation. This ensures that the result is not distorted by too long or short fibers, despite the uniform subdivision by the regions. In every region of an octree level each characteristic of a fiber is weighted with its coverage and divided by the total amount of fibers inside the region to compute a scalar. The calculation of the scalar for region j , results from the value of a fiber characteristic x_i (= Length, Diameter, Volume,...) and the calculated weight w_i as average value, which can be seen in Equation 5.2.

$$\bar{x}_j = \frac{1}{FibersInRegion} * \sum_{i=1}^{FibersInRegion} x_i * w_i \quad (5.2)$$

The scalar values from each region are then used and mapped to a color using a color transfer function. A diverging color scheme was used to better highlight the regions with values above or below the average, and the colors were selected with the "ColorBrewer" [aPS] tool. The colors were chosen to give a robust and easily distinguishable color scheme for the cubes and remain recognizable even for color blind users. The color legend can be seen in Figure 5.4. This makes it possible for the user to detect homogeneous as well as heterogeneous distributions in the regions by their color coding.

Maximum Intensity Projection

To give the user a quick way to evaluate the MiM's 3D heatmap in a certain viewing direction a Maximum Intensity Projection (MIP) is displayed. In the MIP technique, parallel rays are sent through a volume and its voxels, which store a intensity value. The highest intensity of all voxels along this ray is picked and displayed as a new voxel. In our approach the individual voxels are the regions defined by the current octree level in the fiber volume. Each of these regions has its weighted average value stored for each of the fiber characteristics. Parallel rays, aligned with the volume, are sent through the regions and the highest average value is used for the visualization method. The rays are

sent along the X-axis, Y-axis, and Z-axis, each in positive and negative direction. Of the six possible projection planes, only three are calculated because the two directions along the same axis give identical results. As a result, the highest average value of each row or column, consisting of several regions, is projected to a single value for the respective row or column on the MIP plane. The Maximum Intensity Projection along the Z-axis direction can be seen in illustration 5.5.

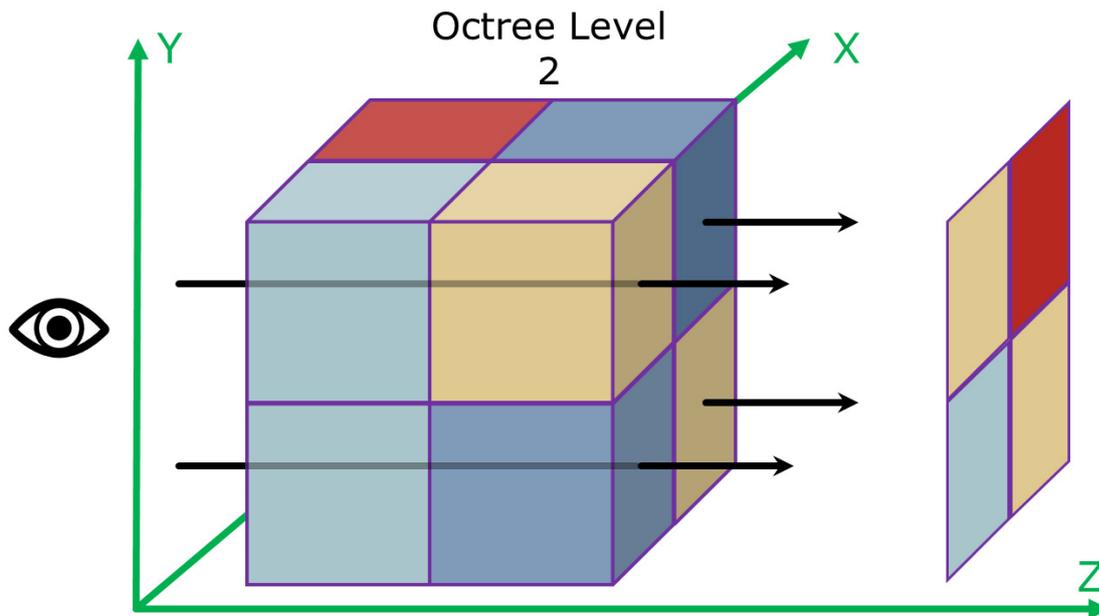
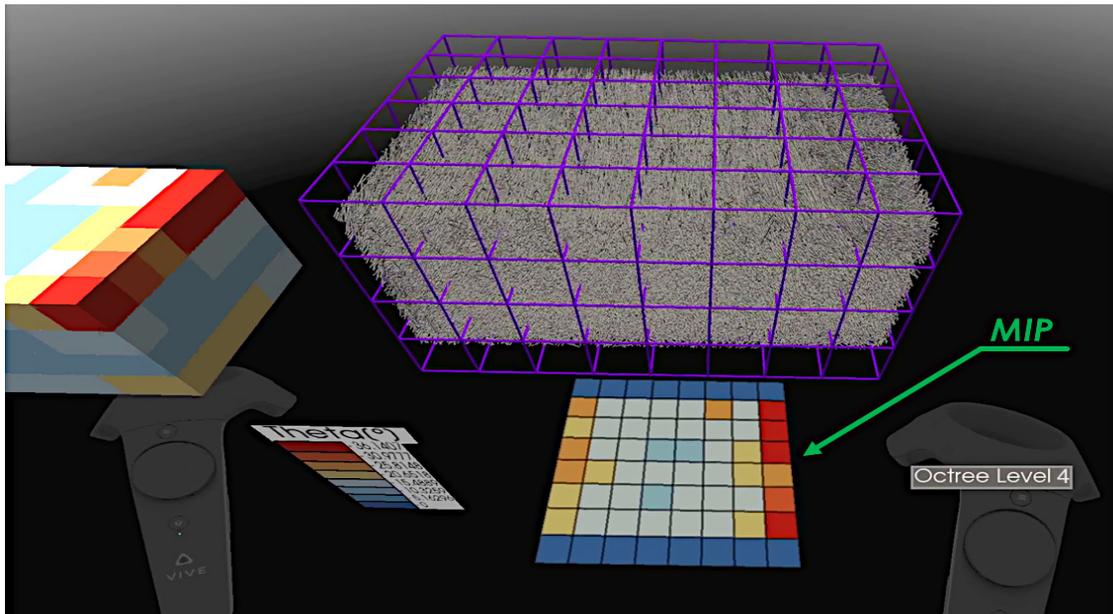


Figure 5.5: Illustration of our Maximum Intensity Projection. In this example, rays are sent through the rows of regions parallel to the Z-axis. The highest average value of a fiber characteristic along the Z-axis in each row is finally projected onto a new 2D surface.

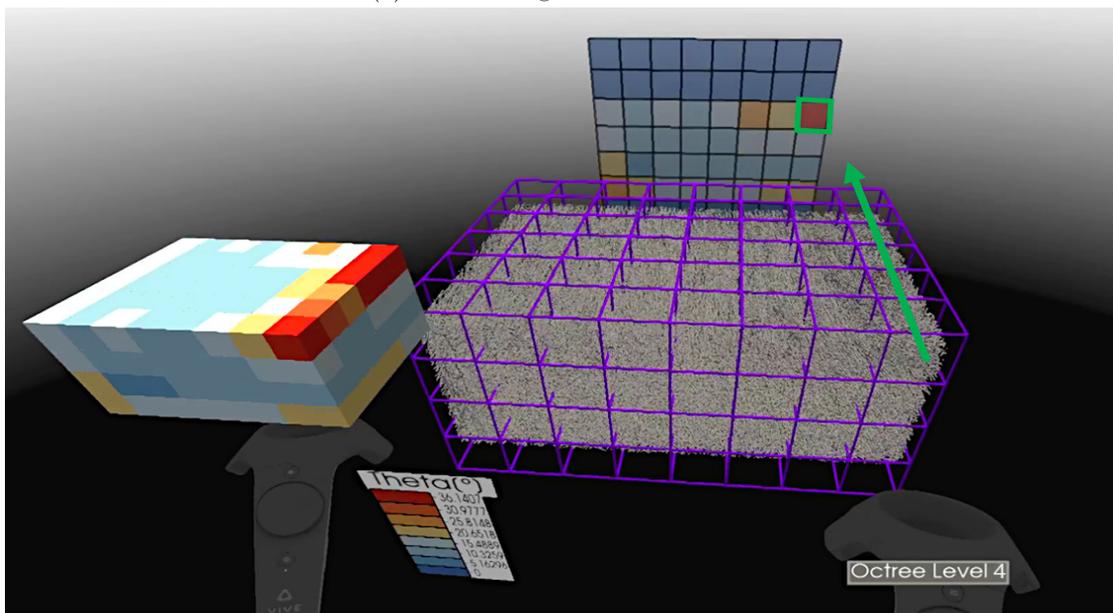
The MIP allows the user to determine the largest average value of a fiber characteristic along an axis direction by a 2D projection. This provides an estimate of the approximate average value of regions within the volume that are hidden by other cubes in the MiM. The user gets the MIP visualized in his current viewing direction as a 2D surface parallel to the fiber volume. The respective MIP plane is displayed behind the volume depending on the user's viewing direction, as shown in Figure 5.6. The user's view along the negative Y-axis can be seen in Figure 5.6a. Figure 5.6b shows the view following the negative Z-axis. The MIP is always visualized in the user's direction behind the volume. The user can also make the fibers in the volume transparent in order to look through the volume and determine the cube row with the highest color value. In the images of Figure 5.6 it is also possible to identify a blue border in the MIP. Increasing the octree level can lead to regions in the volume where fibers are no longer present. To give a correct representation of the MIP plane, rays are also sent through empty regions that are not visible as purple border in the volume. This means that the border regions of the spatial octree have no

fiber coverage and therefore their maximum value is set to zero. Since the color scheme used in this example has blue as its lowest value, these areas are colored blue in the MIP. The MIP therefore retains its quadratic (same number of rows and columns) shape even when regions are empty in the volume. Derived from the respective octree level L , the regular grid resolution G of the MIP can therefore be calculated using Equation 5.3.

$$G = 2^{L-1} \times 2^{L-1} \tag{5.3}$$



(a) Look in negative Y direction.

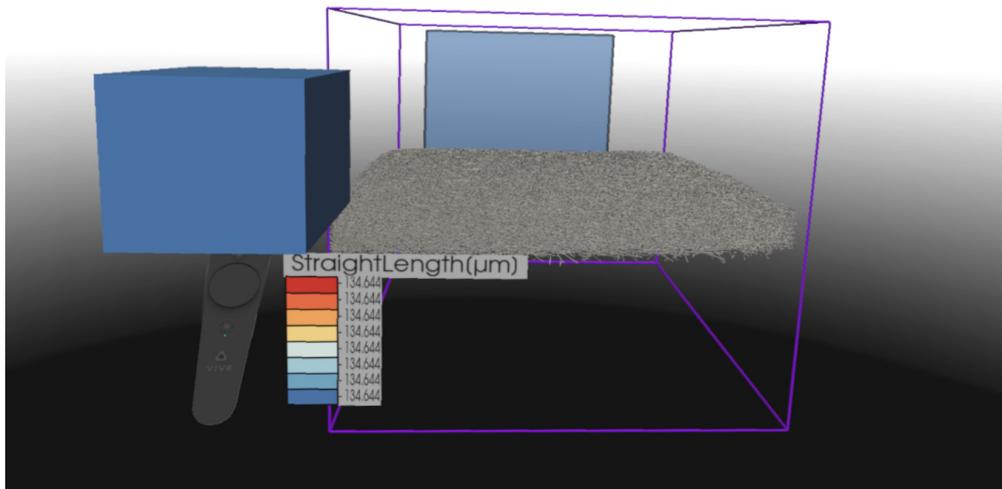


(b) Look in negative Z direction.

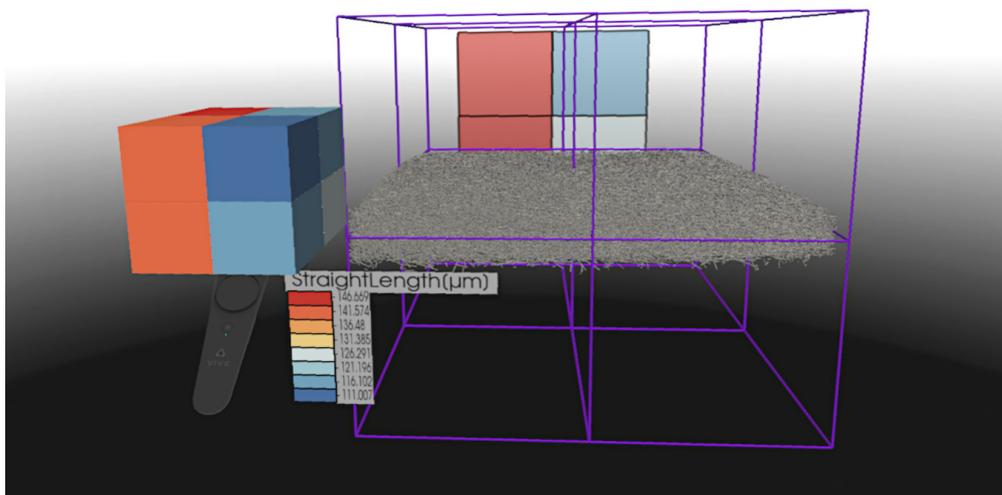
Figure 5.6: Two of the six possible Maximum Intensity Projection directions of the volume. In (a) it is visible how the upper right row of regions in the volume show high values (red color) in the MiM. This is shown in the MIP as well, as red squares in the respective row. In (b) these high values of the regions can be observed in negative Y direction, which yield a red square in the MIP. The annotations in green were included as a description and are not shown in the application.

5.4.3 Spatial Filtering

After the possibility to get an general overview via MiM and MIP and discovering interesting areas in the volume the next exploration step is a filtering interaction. The first way to influence the exploration is to change the currently selected fiber characteristics. Using a controller action, the user can switch the currently displayed fiber characteristic. This enables the user to view different characteristics of the fibers on the MiM as a 3D heatmap. Every change due to user interaction updates the MiM and its visualization. To analyze the displayed distributions, in the 3D heatmap, of similar or dissimilar regions, a spatial filtering is necessary. Changing the octree level subdivides or merges the currently displayed regions, depending on whether the user increases or decreases the octree level. By increasing the octree level, the three-dimensional regions of the volume become smaller and therefore contain fewer fibers, which allows the user to obtain more detailed information. The 3D heatmap of the MiM, as well as the fiber Volume adapts to these changes. As shown in Figure 5.7 and Figure 5.8, changing the octree level can reveal patterns that were hidden in the previous levels of the volume or 3D heatmap. It is therefore possible at any time to view the fibers visually in the volume, in different octree levels, and also examine the characteristic's mean value of the regions in the MiM as 3D heatmap. In order to better recognize the more detailed regions and reduce possible occlusions, regions in the volume without fibers are hidden in the MiM and the volume. Thus exploration is not disturbed and deeper regions are not covered by previous levels. Figure 5.7 and 5.8 shows some of the mentioned effects and techniques. For example, Figure 5.7a shows a very narrow volume in the first octree level. Since the octree structure must be square, the Bounding Box is as high as it is wide, which explains the empty area above and below the volume. Two octree levels higher in Figure 5.8a the blue border in the MIP can be seen as most of the upper and lower areas are without fibers as previously described. The regions belonging to the blue areas are hidden and therefore not visible in the MiM and volume.

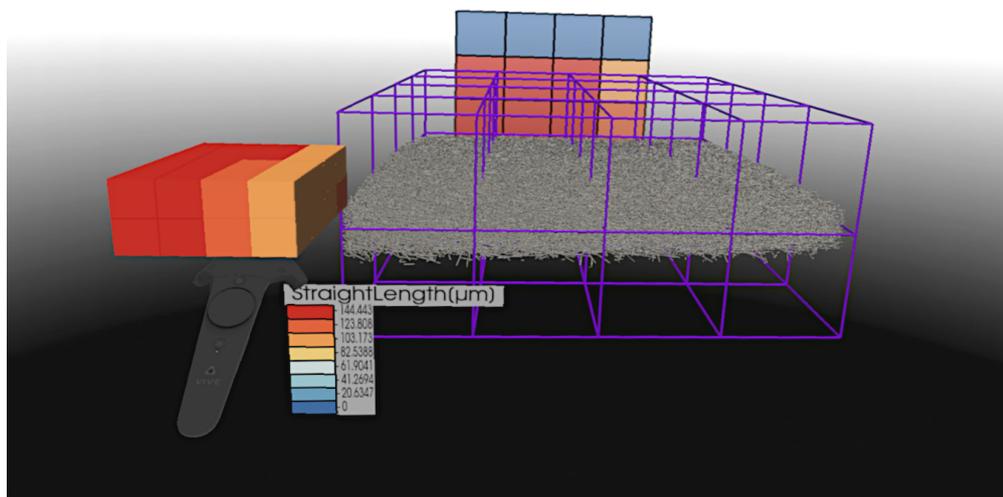


(a) Octree level one.

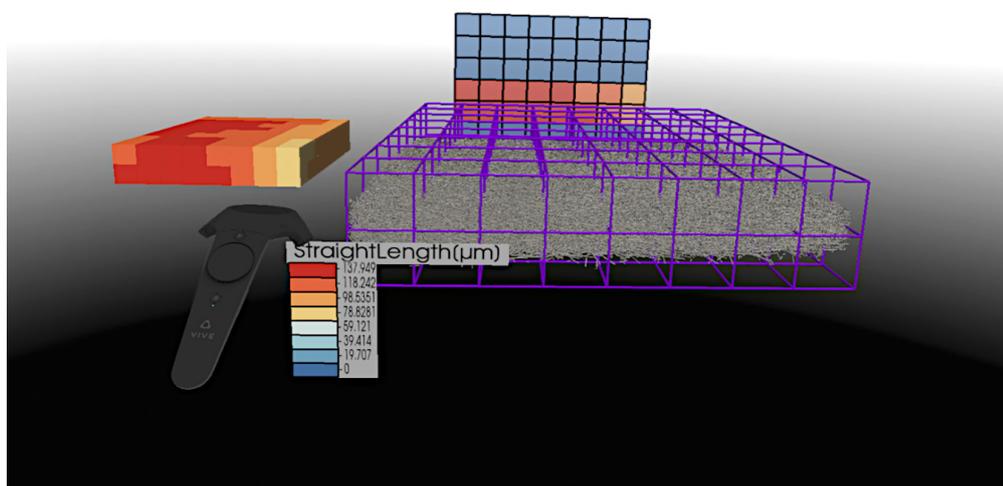


(b) Octree level two.

Figure 5.7: The volume in level one (a) consists of the equilateral bounding box. By increasing the octree level the subdivision of the volume and thus the MiM is increased evenly (b).



(a) Octree level three.



(b) Octree level four.

Figure 5.8: Further division of the volume (a-b), which makes the regions smaller, the calculation more accurate but results in empty regions without fibers. The empty regions are hidden in the volume and the MiM, but can be seen in the MIP.

In order to analyze the fibers of one or more regions in more detail, an additional interaction is available. The framework offers the possibility to select regions in the MiM as well as directly in the volume. Simple selection requires an action at the controller, which allows the user to select a region by pressing a button. This region is then highlighted in the MiM, as well as in the volume with a border. Furthermore, the fibers in the selected region are highlighted in red. The remaining, not selected, fibers are rendered transparently in order not to lose the spatial context. A closer look at the fibers of the selected region due to the reduced clutter is possible, as shown in Figure 5.9. The interaction can be extended to a multiselection. Two or more regions can be selected by pressing and holding a key, which again highlights the fibers in every representation. The MiM and the volume are therefore linked views, which react to interactions simultaneously. All these factors help the user to keep the overview and to strengthen the connection between the abstract MiM and the fiber volume during the exploration.

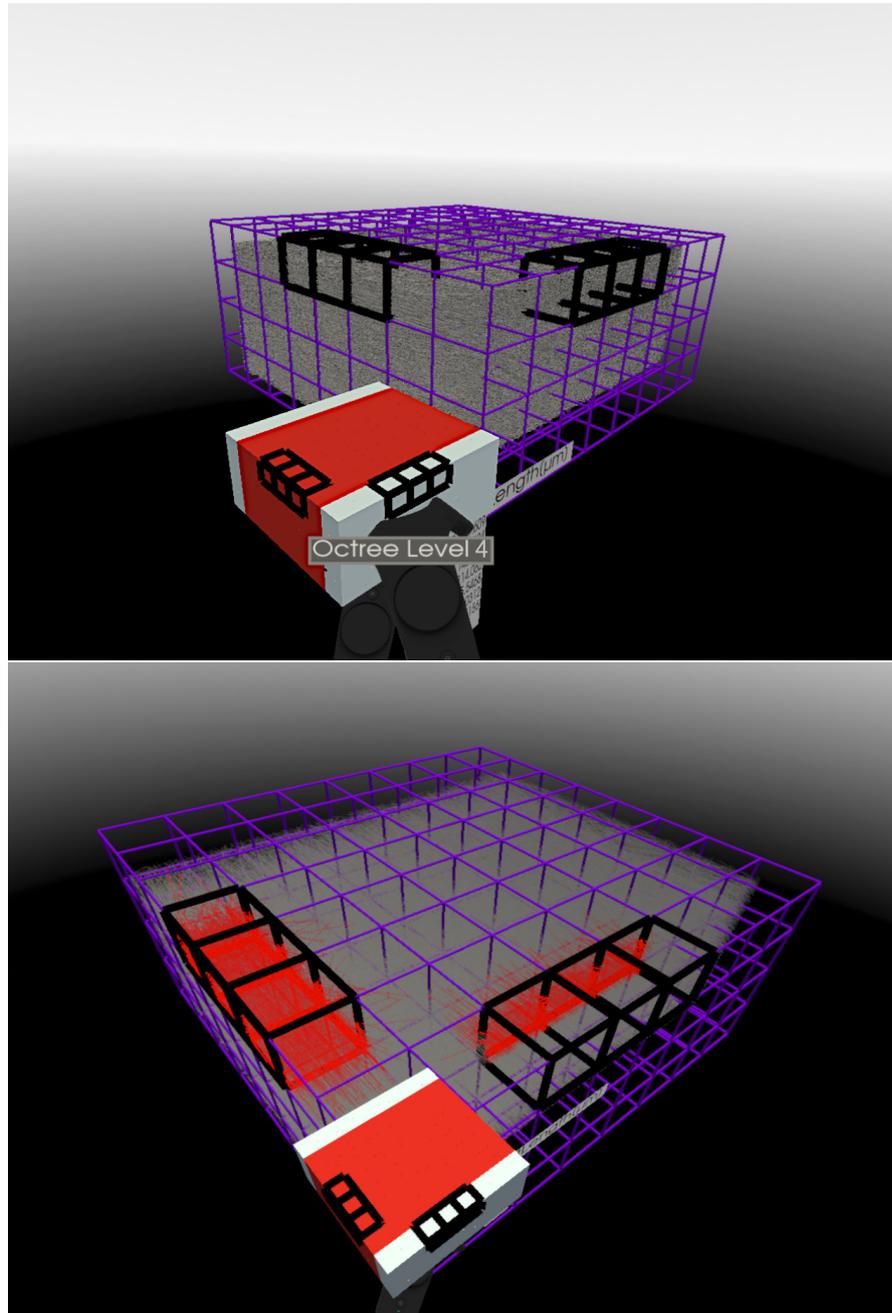


Figure 5.9: Selection of multiple regions, which are marked in the MiM as well as in the volume. The corresponding fibers in the selected regions are highlighted in red and the remaining fibers are rendered semi-transparently.

5.4.4 Detailed Exploration

After the overall view, which can be adjusted by spatial filtering, the MiM can also be used to explode the displayed volume in order to view specific details. The technique we use here is often called Exploded View. Exploded Views are used in different domains [Gr6, RVB⁺08, SMW⁺19] in order to get a non-obstructed view of interior objects in focus. The technique is mostly used for objects, in which the structure, or the context of its components is important. Here, approaches like cut aways are not applicable, because important information and local relationships are lost. Since fiber-reinforced polymers can consist of more than tens of thousands of fibers, exploding the volume allows a reduction in occlusion. In addition, the MiM is also simultaneously exploded, which makes it easier to select its interior. Since the spatial context is of great importance in material science, our method aims at preserving the global structure of the volume, but displaces the individual regions of the volume and the MiM to allow a more detailed analysis. Different types of explosions are used to decompose the volume and its abstract representation by structural step-by-step views. As the relationship between the regions and their fibers is of great interest to experts, our shifts can be applied in individual steps. Thus, in a step-by-step procedure, the individual shifts can be applied or undone and followed in detail. For this purpose we are using a relative, a linear, and a so called eight-region displacement with a predefined offset. All these displacement types, explained below, can be combined to create unique decompositions. Each shift can be individually applied or undone step by step, to make the changes in the fibers visible.

Relative Displacement

The relative displacement allows the regions to drift apart equally. The direction \vec{d}_i from the center of the octree $\overrightarrow{orig_0}$, i.e., the center of the bounding box of octree level one, to the center of each region $\overrightarrow{orig_i}$ is calculated. The maximum distance D_{\max} of all distances $|\vec{d}_i|$, where $|\cdot|$ is the length of a vector, is stored. Then all regions are shifted by the offset C , which is weighted with the distance $|\vec{d}_i|$ in relation to the maximum distance D_{\max} . In both volume and MiM, each region is moved to its new position $\vec{P}_{i_{new}}$ from the region's center in the direction $\|\vec{d}_i\|$, where $\|\cdot\|$ defines the normed direction. This can be formalized as follows:

$$D_{\max} = \max_{i=1,\dots,n} (|\vec{d}_i|) \quad (5.4)$$

$$\vec{P}_{i_{new}} = \overrightarrow{orig_i} + (\vec{d}_i \cdot \frac{C}{D_{\max}}) \quad (5.5)$$

By moving each region by the same amount C depending on the region's distance to the octree center, as shown in Figure 5.11a, the spatial structure is preserved and provides the opportunity to view the inside of the volume.

Linear Displacement

During the linear displacement all regions of the MiM and volume are shifted by the same offset C . The normed direction $\|\vec{d}_i\|$ is used for this. This leads to cubes closer to the octree center being moved further away than those more distant. The offset therefore contributes less to the displacement of more distant regions. This results in a radial shift, which is expressed by formula 5.6.

$$\vec{P}_{i_{new}} = \overrightarrow{orig}_i + (\|\vec{d}_i\| \cdot C) \quad (5.6)$$

The radial shift now slightly changes the structure, but enables a greater visibility into the interior of the volume, which can be seen in Figure 5.11b.

Eight-Region Displacement

With the eight-region displacement the volume and MiM is shifted in by the 8 octants, which are defined by the three axial planes X, Y, and Z. The center of the coordinate system is assumed to be the center of the octree \overrightarrow{orig}_o . Each region center point \overrightarrow{orig}_i is moved towards the axial plane of the three-dimensional octant, in which the region is located. These octants are illustrated in Figure 5.10. The displacement is calculated by determining for each region of the volume the octant (I to VIII), in which it is located and then moving the center of the region by the offset C in the direction of this octant. The displacement can be formalized as follows:

$$\overrightarrow{orig}_o = \begin{pmatrix} o_x \\ o_y \\ o_z \end{pmatrix} \quad (5.7)$$

$$\begin{array}{l}
 \vec{orig}_i \in I : \quad \forall x > o_x, y > o_y, z > o_z \\
 \vec{orig}_i \in II : \quad \forall x < o_x, y > o_y, z > o_z \\
 \vec{orig}_i \in III : \quad \forall x < o_x, y < o_y, z > o_z \\
 \vec{orig}_i \in IV : \quad \forall x > o_x, y < o_y, z > o_z \\
 \vec{orig}_i \in V : \quad \forall x > o_x, y > o_y, z < o_z \\
 \vec{orig}_i \in VI : \quad \forall x < o_x, y > o_y, z < o_z \\
 \vec{orig}_i \in VII : \quad \forall x < o_x, y < o_y, z < o_z \\
 \vec{orig}_i \in VIII : \quad \forall x > o_x, y < o_y, z < o_z
 \end{array}
 \vec{P}_{i_{new}} = \left\{ \begin{array}{l}
 \vec{orig}_i + \begin{pmatrix} C \\ C \\ C \end{pmatrix}, \vec{P}_x \in I \\
 \vec{orig}_i + \begin{pmatrix} -C \\ C \\ C \end{pmatrix}, \vec{orig}_i \in II \\
 \vec{orig}_i + \begin{pmatrix} -C \\ -C \\ C \end{pmatrix}, \vec{orig}_i \in III \\
 \vec{orig}_i + \begin{pmatrix} C \\ -C \\ C \end{pmatrix}, \vec{orig}_i \in IV \\
 \vec{orig}_i + \begin{pmatrix} C \\ C \\ -C \end{pmatrix}, \vec{orig}_i \in V \\
 \vec{orig}_i + \begin{pmatrix} -C \\ C \\ -C \end{pmatrix}, \vec{orig}_i \in VI \\
 \vec{orig}_i + \begin{pmatrix} -C \\ -C \\ -C \end{pmatrix}, \vec{orig}_i \in VII \\
 \vec{orig}_i + \begin{pmatrix} C \\ -C \\ -C \end{pmatrix}, \vec{orig}_i \in VIII
 \end{array} \right.$$

(5.8)

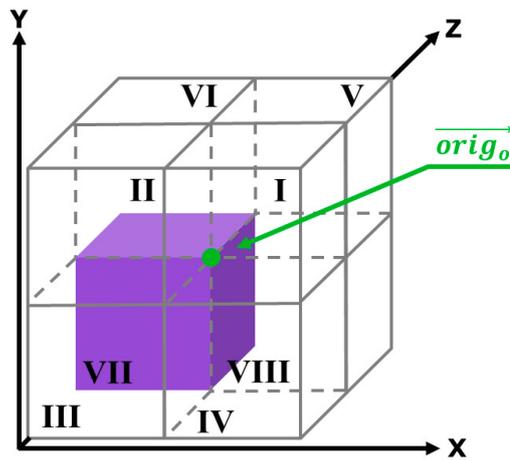
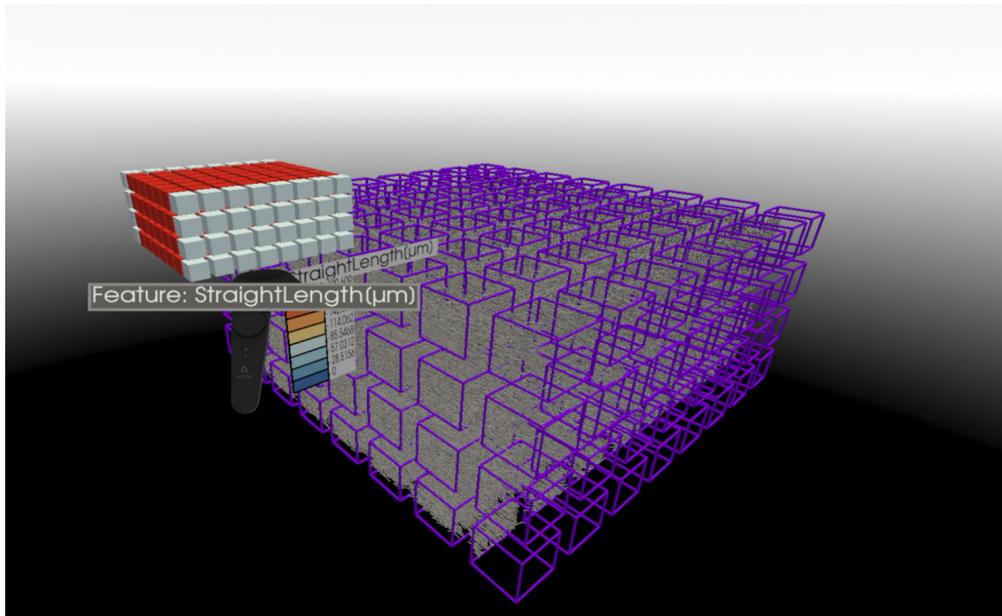


Figure 5.10: The eight octants of the 3D euclidean coordinate system. In green the center point of the coordinate system is marked.

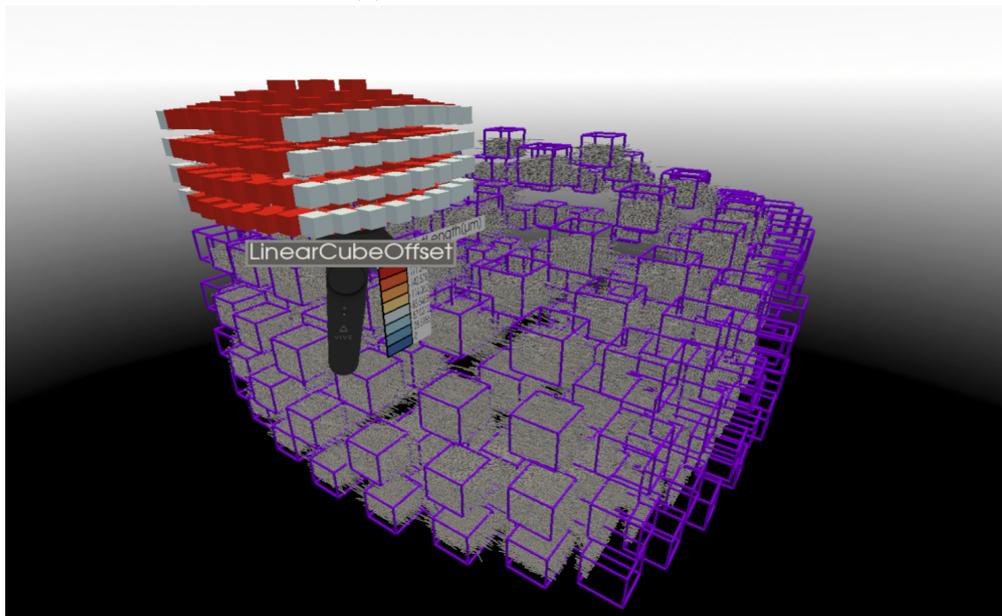
This displacement allows to preserve the structure of the volume while decomposing it in a way that enables a view of the inner regions. The resulting displacement can be seen in Figure 5.12a.

Hybrid Displacement

The combination of the three implemented displacements provides a fourth form of hybrid displacement, which can be seen in Figure 5.12b. The combination of the described displacement methods allows the user to freely move certain areas so that a detailed, uncluttered exploration can be performed. This allows for very unique displacements which can lead to previously impossible insights into the volume.

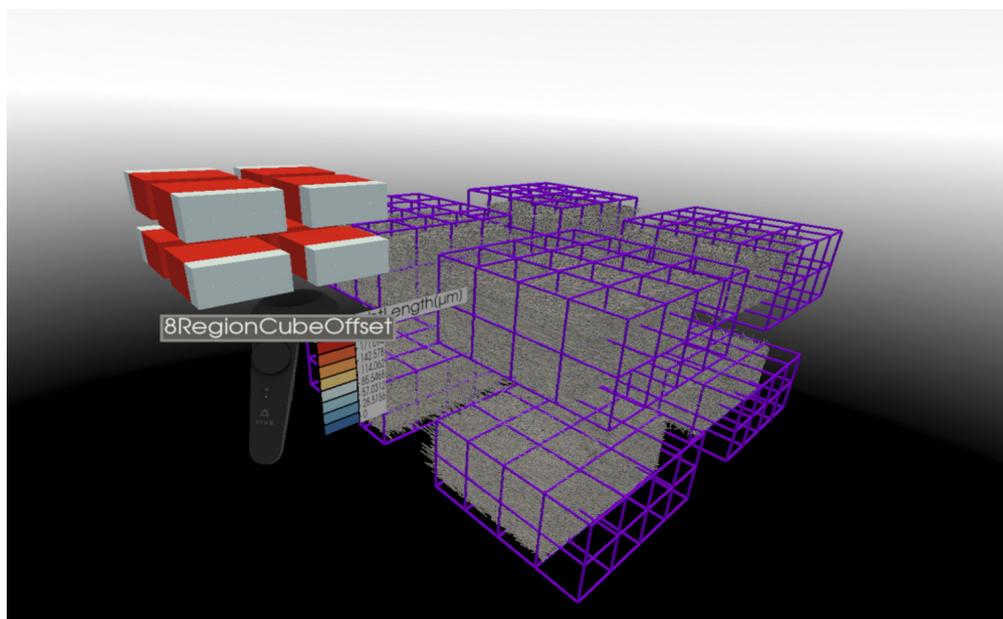


(a) Relative Displacement.



(b) Linear Displacement.

Figure 5.11: The user has the possibility to choose between three different modes to explode the volume. In (a) the regions in the MiM, as well as in the volume, are shifted relatively which preserves the overall structure of the volume. The linear shift (b) gives a better look into the interior of the volume but changes the structure slightly.



Fiber Displacement

Our exploded views also provide the ability to cluster the dataset. This clustering results from the specific way, in which the fibers are moved with the exploded regions. The direction in which the regions are shifted is determined by the displacement methods we have presented. In order to move the fibers along with the regions, it must be clarified to which regions each fiber belongs. However, the affiliation of the fibers is not clear, since a fiber can traverse through several regions and thus no trivial shifting is possible. In order to ensure an intuitive fiber displacement that preserves the spatial structure and context of the fiber volume, two different fiber displacement techniques have been developed. First, the displacement selected by the user is applied to the regions of the volume and the cubes of the MiM. The applied offset C is later also used for the fiber displacement. The percentual coverage of each fiber serves as connectivity information for the respective regions and determines how the fibers are shifted with the regions. The two methods described below determine for each fiber which region(s) are targeted for the shift and apply the formulas of the displacement techniques to the start and end points of the fibers for these selected regions.

Method one uses the coverage values of the fiber for each region it traverses. The fiber is shifted in the direction of each region where it has a coverage greater than zero. For each region, the offset for the displacement is multiplied by the percentage of fiber coverage in that region. This means that the fiber is shifted to a greater extent in the direction of regions in which it has higher coverage than in the direction of regions in which it has less coverage. As a result, sometimes a very uniform change is possible in which the fibers shift only slightly and no significant cluster effects are visible. This is because when fibers are shifted with two regions that are displaced in opposite directions, the fiber moves only marginally as the opposite displacement offsets can cancel each other out.

Method two is based on the maximum coverage of a fiber. For each fiber, the highest coverage from all regions is determined, which is then representative for that fiber. If a displacement is used, the fiber is only shifted in the direction of the region where it has the highest coverage. This method of fiber displacement preserves the spatial structure and context of the fiber volume, since only one region is considered for the displacement of each fiber. A further advantage results from the fact that due to the displacement method, regions only consist of fibers which have their greatest coverage in these regions. This also results in well visible cluster formation and is therefore used as standard. The maximum fiber coverage method can be seen in Figure 5.13.

The displacement of the fibers by their coverage in the regions of the volume creates therefore a form of clustering. This clustering becomes more obvious when regions are selected. During selection, all fibers, that start, end, or pass through the selected region, are highlighted in red. After a shift, fibers may be highlighted in red that are not located in the region selected by the user. This indicates that the coverage of these fibers was higher in another region and therefore they moved with another one. Therefore, the

exploded view can be used in combination with a selection to investigate certain clustering patterns in the fiber dataset.

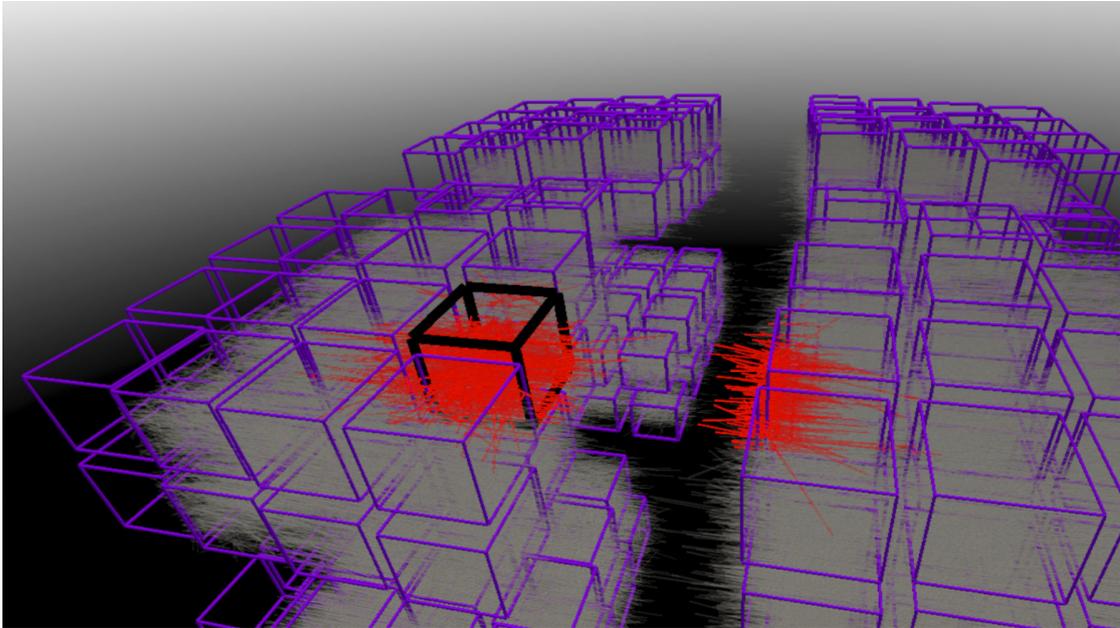


Figure 5.13: The volume was displaced by a relative shift and the eight-region shift method. The user has selected a region on the left side of the volume, so all fibers passing through this region are marked red. It is clearly visible that some fibers are marked on the right side, because they have a higher coverage in that region, and have been displaced with it.

5.5 Node-Link Diagram

Another visualization technique implemented in the presented system is the node-link diagram, which is intended as an alternative representation to offer an overview of the volume structure and to allow the user to filter for relationships between the regions. As briefly mentioned in Chapter 3, this visualization technique is a promising form of representation in the field of Immersive Analytics. It supports the understanding of the overall structure of complex fiber-reinforced polymers and enables the acquisition of new insights that are only possible through the immersive perspective [SWKA19].

5.5.1 Overview Exploration

Through a controller action, the entire volume with the current octree division can be transformed into a node-link diagram. Each region in the volume is replaced by a cube and the fibers are hidden. The size of the whole cube and its color indicate the number of fibers it contains. The cubes are connected by lines that represent the

relationship between the regions. Both color and size are chosen to encode the strength of the relationship. The cubes represent the nodes of the diagram and the lines represent the links, thus creating a node-link diagram. Large, bright white cubes indicate a high number of fibers relative to the region with the most fibers, and small dark purple region indicate regions with less fibers. This gives the user a quick overview in which areas the distribution of fibers is denser, since there several neighboring regions will be shown as large bright cubes. Thicker bright orange lines between the regions mean that these regions have many fibers in common, i.e. that they have a strong relationship to each other. To ensure visually noticeable coding even for very small differences, we use exponential mapping for the values of nodes and links. We have chosen two encodings for the same attribute for both nodes and links to compensate for any perspective distortion. Although perspective distortion is an important depth cue, it can cause problems when interpreting sizes, which is why we have chosen to add color. Regions further away from the observer become smaller due to the linear perspective, so their size cannot always be estimated correctly. This is where encoding with color helps to prevent misinterpretation. The visualization can be exploded to reduce potential clutter and facilitate selection tasks. It is also beneficial in combination with the linear displacement method, as it allows the node-link diagram to be positioned radially around the user. A demonstration of the technique can be seen in Figure 5.14.

5.5.2 Spatial Filtering

To provide a quick overview, all displayed fibers of the volume are hidden when switching to the node-link view. Therefore the cubes representing the regions now indicate the number of fibers with their size and color. Next, the user can switch between the displayed relations by a controller action. The pairwise links between the regions i and j represents the number of fibers they share. The links are drawn between each cube as long as there is a similarity. This metric is calculated by using the Jaccard index presented in Equation 5.9.

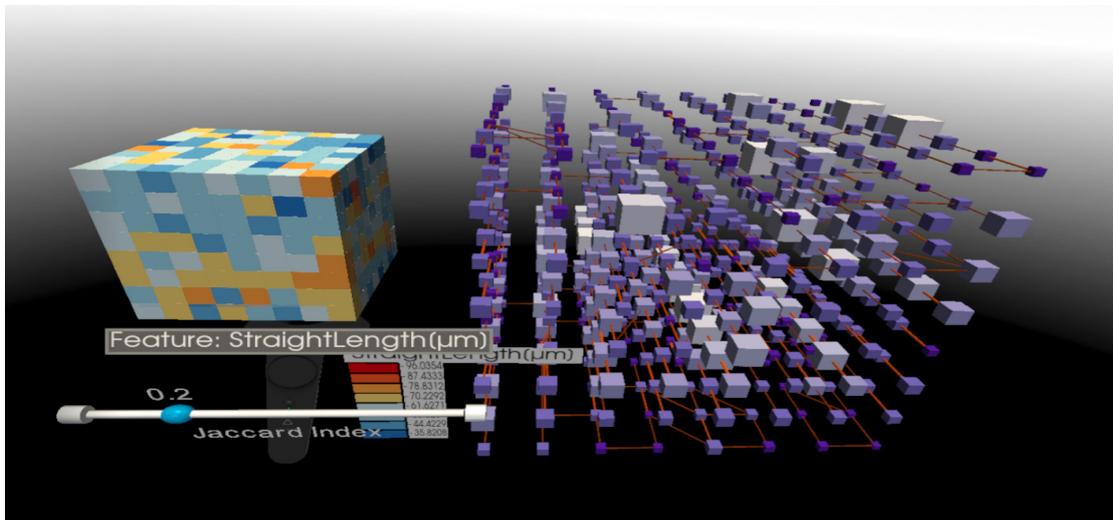
$$J(i, j) = \frac{|i \cap j|}{|i \cup j|} = \frac{|i \cap j|}{|i| + |j| - |i \cap j|} \quad (5.9)$$

$$(5.10)$$

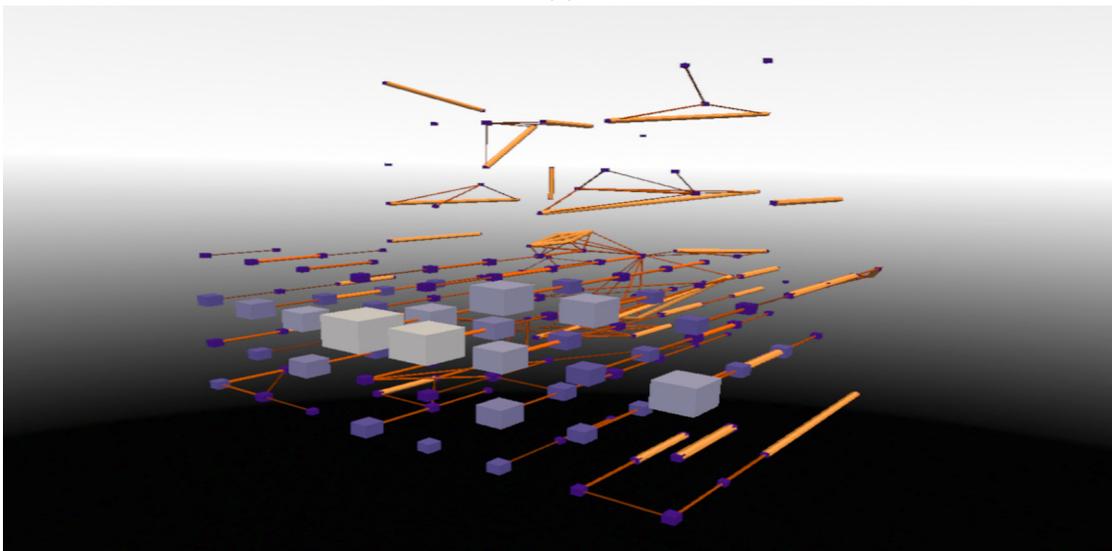
$$0 \leq J(i, j) \leq 1 \quad (5.11)$$

The Jaccard index is used to find similarities between finite sets of samples. In our work we compare all regions with all other regions to calculate their similarity or dissimilarity. The resulting value ranges from zero to one and indicates how many fibers these regions have in common. This value is interpreted as a similarity between two regions from 0 percent to 100 percent. 0 percent means that both regions do not share any fiber and 100 percent that they consist of the same fibers. This value is mapped as the radius of the link. In this representation, interesting patterns in the neighborhood can be

discovered. For example, many horizontal lines between nodes and few vertical lines mean that the primary fiber orientation must be horizontal. In other words, many horizontal relationships mean that long fibers traverse horizontally across several regions and thereby connect them, which is expressed by a Jaccard index above zero. The Jaccard index can be thresholded allowing the user to show only links above a certain percentage. This allows the user to reduce any clutter caused by too many links through the filter interaction. The user has the possibility to filter for specific relationships and explore the dataset through the node-link representation to find spatial patterns.



(a)



(b)

Figure 5.14: Volume displayed as a node-link diagram, in which size and color of the nodes and links are encoded. In (a) it is visible that the cubes are very similar in thickness (their volume) and color, which indicates a very homogeneous fiber distribution of the volume. A very heterogeneous volume can be seen in (b). Here, denser fiber regions can be seen and also regions that share many fibers, which can be seen by the brighter and thicker links. Regions without fibers are hidden.

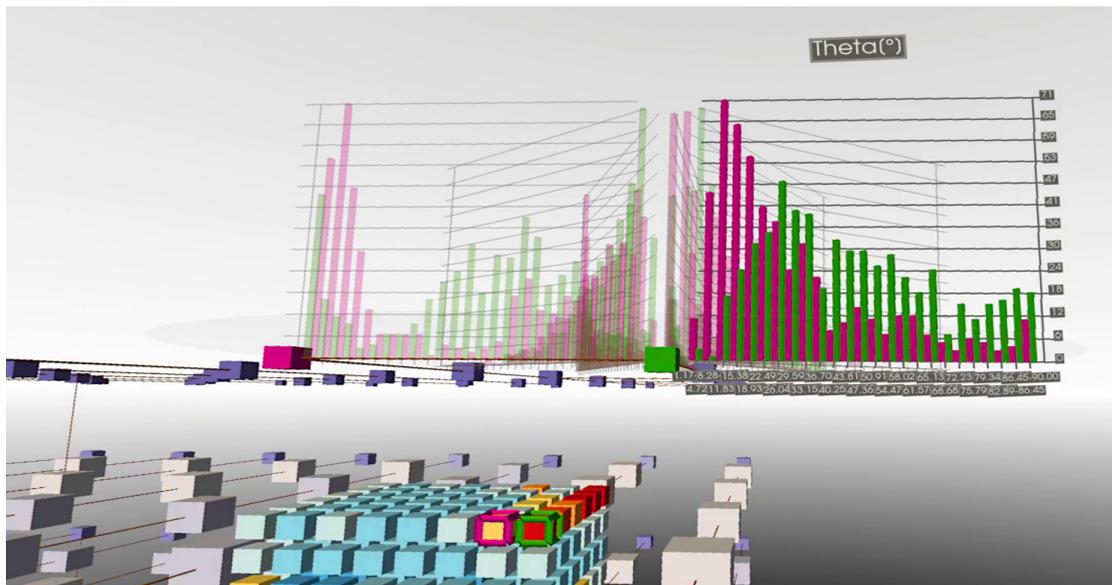
5.6 Histogram

In our application, the user has gained an overview of the volume with its fibers. It was also possible to intuitively filter and view the regions in more detail, using a new interaction technique called MiM. Furthermore, it was possible to abstract the representation by a three-dimensional node-link diagram to emphasize relationships between regions. Finally, it is of interest to investigate the distribution of the fiber characteristics. For this purpose, a three-dimensional histogram is available as a visualization technique to view the specific distribution of the data.

5.6.1 Overview Exploration

The user has the possibility in the node-link representation to examine the feature distribution of two regions more closely. It is possible to select two regions via the MiM, after which they are highlighted and a histogram calculation of the values in these two subvolumes occurs. The 3D histogram is then rendered at the first selected cube. For the color coding of the histogram, strong contrasts, in relation to the environment, were used to support the exploration of the visualization. To give the user a spatial reference, the colors of the two regions are marked in both the MiM and the node-link diagram. In MiM the region is marked with a border in the respective color and in the histogram the bars are colored accordingly. The user is shown a semi-transparent circular area, in which, within a half-circle, the individual distributions are displayed, as shown in Figure 5.15. The visualization technique follows a book metaphor. The first two distributions of fiber characteristics are shown on the two front pages of the opened book. The user's point of view determines which page is currently highlighted, the remaining histograms in the circular layout are displayed semi-transparently. This ensures that the user is not irritated and distracted by too many distributions and that only the feature of interest is in focus. The other histograms are less dominant, but remain perceptible, so that the user can still get an overview of the remaining characteristics of the fibers.

This visualization method is well suited to quickly verify hypotheses. When looking at the representation, the distribution with its maxima and minima can be seen at a glance. On the vertical axis the number of fibers (observations) are plotted. Therefore tall bars indicate a high number of similar fibers in the region. To better estimate the bar height and to reduce the effects of perspective distortions, horizontal lines are displayed to emphasize a certain number of fibers in the region. The horizontal axis is divided into bins with equal distances. The values increase from the center of the circle (starting point of the diagram) to the outside. The labels orientate themselves towards the observer in order to make it possible to look at them from every position and every angle. Furthermore the labels are divided into two rows to represent large numerical values without too much overlap. By tilting the head, the labels can also be read in case of occlusion.



(a)



(b)

Figure 5.15: By selecting two regions (a) in the MiM, a more precise visualization can be created to analyze the distribution of fiber characteristics. In (b) the semi-transparent circular area with a 3D histogram in the form of an opened book is displayed more closely. The height of the bars corresponds to the number of fibers with the value of the attribute displayed on the horizontal axis.

5.6.2 Spatial Filtering

To switch between the desired characteristics and filter by fiber characteristics, the user can interact with the histogram. The interaction is possible in the semi-transparent circular area in which the 3D histogram is embedded. Only half of the circle was used to display the histograms. Due to this design decision, the individual histograms are arranged like book pages, with always two "open pages" parallel to the viewer. To enhance the book metaphor and make the interaction as natural as possible, the user has the ability to flip through the pages, i.e., the histograms like in a book. The interaction makes it possible to grab the pages and with it the currently selected histogram and browse through the pages by flipping to the left or right. During this interaction, the focused histogram, with its bars and labels, always remains highlighted.

5.6.3 Detailed Exploration

The user can compare each region with every other region. With the created 3D Histogram it is possible to examine all characteristics of the two selected regions. To provide a detailed inspection of the histograms, the number of required bins have to be calculated. Bins that are too wide can hide important details about the distribution, while bins that are too narrow are difficult to read in 3D at a distance and can also lead to misinterpretation of the distribution. For the calculation of the number of used bins the Sturges' rule [Sco09] is used, which is shown in Equation 5.12. This rule is widely used with great success in statistics software. In our application it was applied because it quickly computes the number of bins b , which are required for further calculations. Furthermore only the number of observations n is needed as prior knowledge, which we know exactly. In our case this can be determined by the number of fibers in the selected region.

$$b = 1 + \log_2 n \approx 1 + 3.322 * \log_{10} n \quad (5.12)$$

After this procedure the bin width h can be calculated. The bin width groups the value range from minimum value to maximum value into intervals. The interval ranges are selected so that all bins have a defined range. The width is then used for the horizontal axis of the equally spaced 3D histogram. For this purpose, the maximum (*max*) and minimum (*min*) values of each characteristic c are stored for all fibers in both selected regions. The value calculated by Equation 5.13 gives the bin width h_c of a specific characteristic.

$$h_c = \frac{(max_c - min_c)}{b} \quad (5.13)$$

The interval for the individual bins is shown in Definition 5.14.

$$[min_c, min_c + h_c]; [min_c + h_c, min_c + h_c * 2]; \dots; [min_c + h_c * (b - 1), min_c + h_c * b] \quad (5.14)$$

All fibers are then classified into the appropriate bins according to the value x_c of their characteristic. The fibers are separated by Equation 5.15 into the respective bins defined by the interval in 5.14. Finally, the calculated values are used to create a spatially optimized circular 3D histogram, which is drawn around the first selected region.

$$b_i = \left\lfloor \frac{(x_c - min_c)}{h_c} \right\rfloor \quad (5.15)$$

Implementation

The choice of frameworks in IA is very narrow and a number of available systems have already been presented in Chapter 4. For volumetric datasets in the field of fiber reinforced materials there is, to our knowledge, no system available so far. For the development of such an IA application some generic tools like VTK [Kitc] or Unity [Tec] can be used. Both have advantages and disadvantages. VTK offers many features for scientific visualization and supports the representation and manipulation of various 2D plots. The use of three dimensional volumes is limited to small views and especially in VR, VTK offers only limited functionality. Unity has the benefit that the engine is designed for games and therefore has been developed for 3D scenes in VR and AR environments.

In this thesis we used the open source framework `open_iA` [FWS⁺19], which is based on VTK, ITK [Kita] and Qt [QTC]. The decision to choose `open_iA` was made because it supports many data formats through VTK and is well known in the field of material science. Since experts in the field of fiber-reinforced polymers also work with this framework, collaboration was facilitated. Our application uses the FiberScout [WAL⁺14] tool. As described in Chapter 4, the module for `open_iA` allows the user to load .csv files of segmented and classified fiber datasets. It stores the start and end points of a fiber as well as characteristics such as length, orientation and similar, that can be calculated from them. Furthermore, the module can render the fibers as cylinders. The rendering and loading implementations were then adapted and extended for the use in VR.

Our immersive analysis framework was implemented as a module for `open_iA`. The required 3D representation and calculations are developed in C++ and are rendered with VTK. This allows domain experts to use the immersive workspace for fiber exploration and gain additional insights.

Results & Evaluation

I hear and I forget. I see and I remember. I do and I understand.

– Confucius

In this chapter we will demonstrate the outcomes of the Immersive Analytics framework presented in Chapter 5. First we show the typical workflow in our tool for the immersive analysis, then we demonstrate the use of the system in a general scenario. We will look at the individual features and explain their usage for the exploration of a volume. Afterwards we will go into more detail about the results of the user study. We will discuss the strengths and weaknesses of our system, as well as the feedback from the experts.

7.1 Fiber Exploration Workflow

Before presenting the general analysis process of the domain expert, we start with the typical workflow in our immersive workspace. The procedure outlined below is shown in Figure 7.1. After loading a dataset, the user selects a fiber characteristic via interactions. By creating and viewing the MiM and the MIP the user gets an overview of the volume and its values distribution. With this information, certain patterns or regions become visible, which may be of interest for the user. These regions can be inspected more closely by selecting them. If a region is strongly cluttered, the view can be adjusted by different exploded views. This can also be used to create a clustering, which provides additional information. To investigate the structure of the volume and the related regions a node-link diagram can be visualized. For the found, selected, exploded, and structurally investigated region a potential hypothesis can be verified. The user is then able to perform a detailed comparison of two regions. An intuitive 3D histogram allows the user a detailed and quick exploration of the fiber characteristics by providing numerical values.

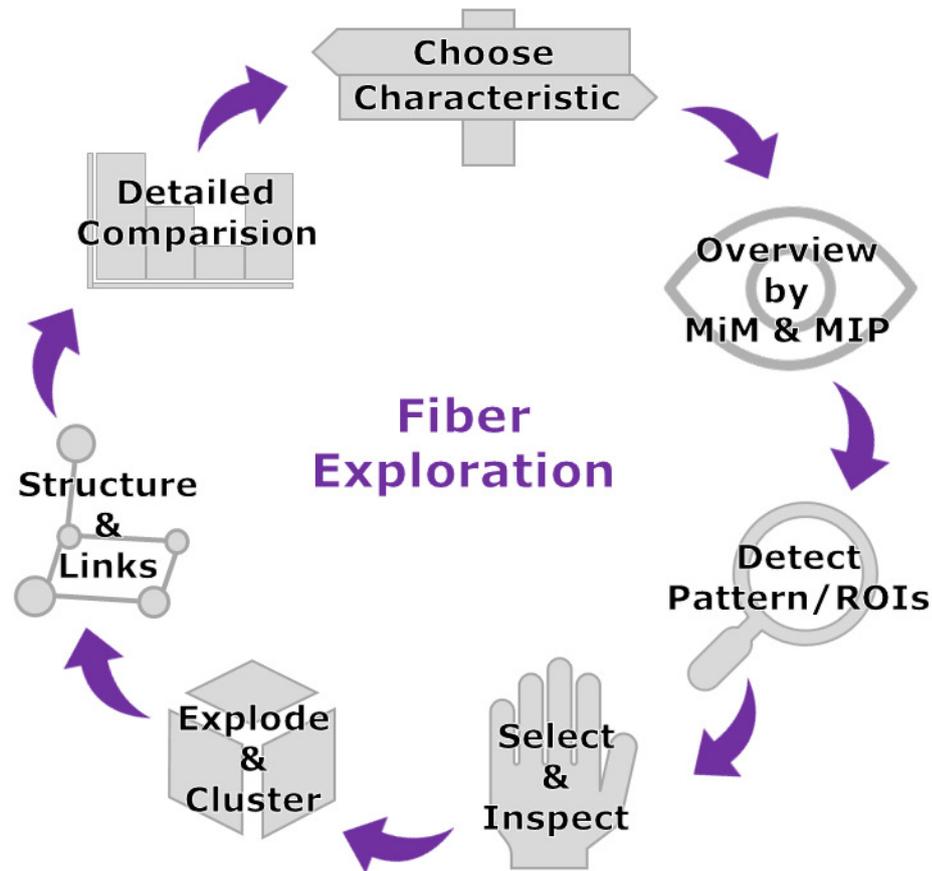


Figure 7.1: Illustration of the basic workflow, which is enabled through our framework. The cycle typically starts, after loading, with the selection of a characteristic.

7.2 Usage Scenario

The dataset, utilized for the use case described above, demonstrates a polypropylene (PP) matrix material, which was reinforced with glass fibers. The volume consists of approximately 19126 glass fibers with different lengths and orientations. The goal of the exploration is to discover unique distributions of fiber characteristics in the volume, in order to support the experts in determining the mechanical behavior of the materials.

The exploration starts with the loading of the dataset. As can be seen in Figure 7.2, the VR module is selected and a .csv file is loaded. Additional calculations or properties of the file can be specified here. If the data is complete and valid, the VR environment is calculated and rendered.

Next, the user sees the volume, which is displayed in octree level one, i.e., contained in a so-called equilateral bounding box, which can be seen in Figure 7.3a. This gives the user

a good overview of the shape and structure of the volume, but due to the huge number of fibers the user may not be able to come up with a rough hypothesis. Therefore the user creates the abstract Model in Miniature, as shown in Figure 7.3b, and chooses a fiber characteristic of interest. Since the user could visually detect strongly changing fiber orientations in this dataset, he selects the attribute "Phi" and is presented with the average orientation for the whole fiber dataset. Now the user knows that on average the fibers have an spherical orientation coordinate "Phi" of about 142 degrees. But, this is still too coarse and therefore the user changes to a higher octree level. As shown in Figure 7.4a, two different regions can be detected. On the one hand, the upper part of the volume is bluish colored and shows areas between 30 and 50 degrees and on the other hand, the lower part of the volume is reddish colored and marks regions with a fiber orientation coordinate between 135 and 189 degrees. This now gives the user an indication of regions of interest. In order to better view the MIP, the user can select any region to make the other regions semi-transparent, or the user can change the viewing angle by moving the head and approaching the MIP. To reduce the variance of the values and to narrow down the regions even more, the user switches to the third level of the octree as shown in Figure 7.4b. Through this investigation the range of values is now defined more precisely and the boundaries of the two different areas of the material are clearly visible.

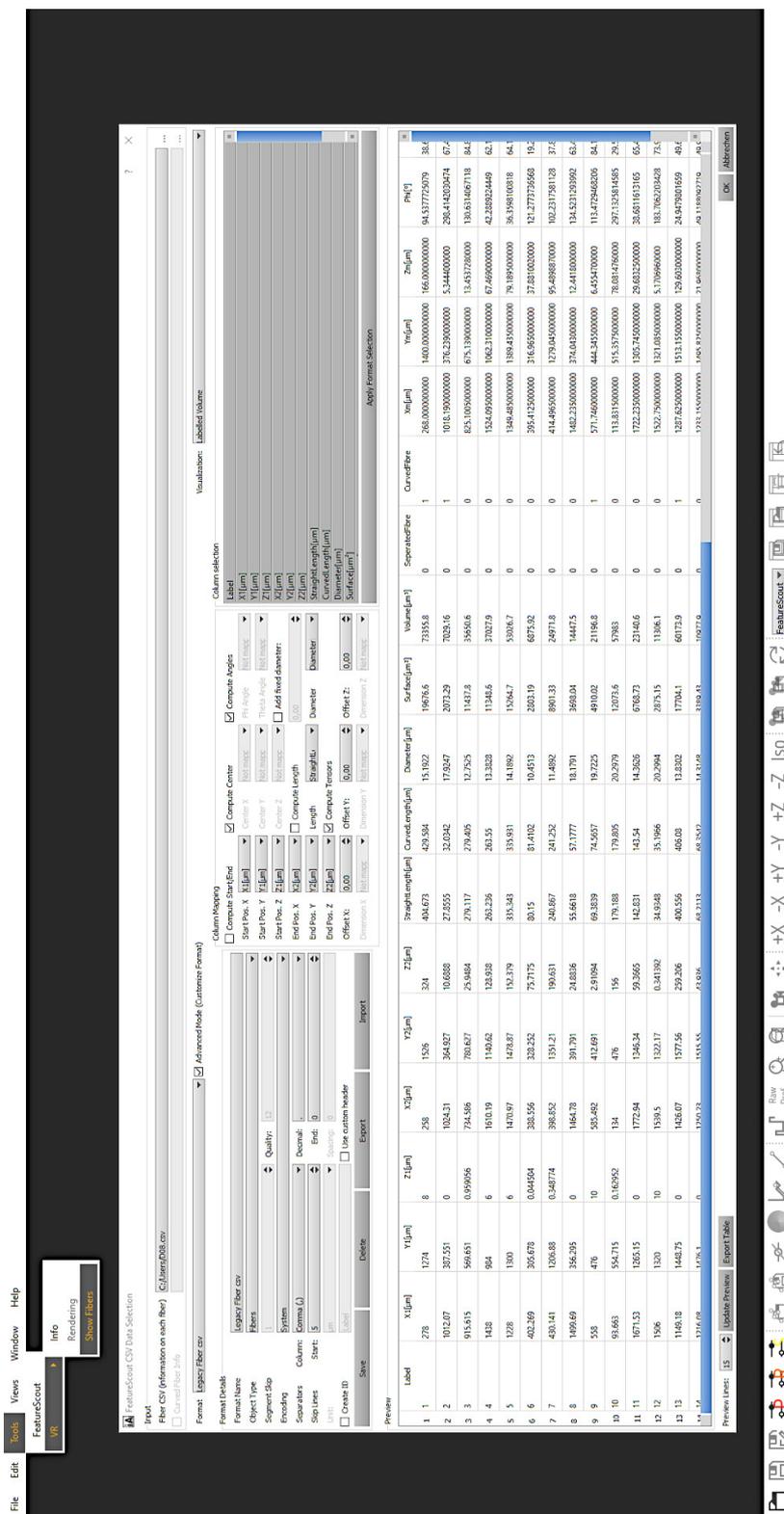
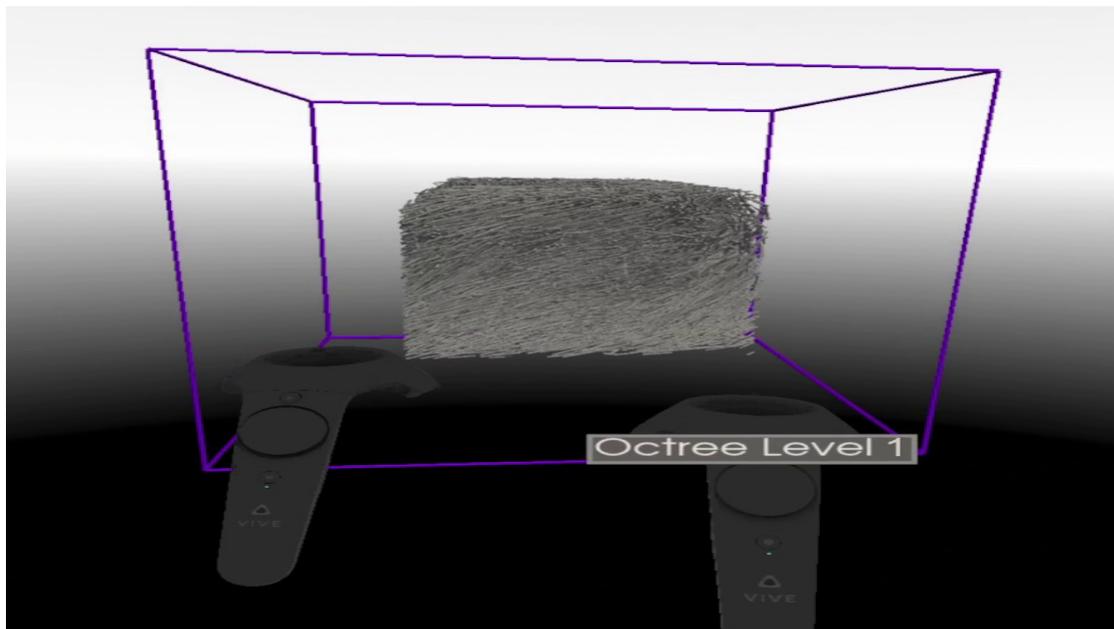
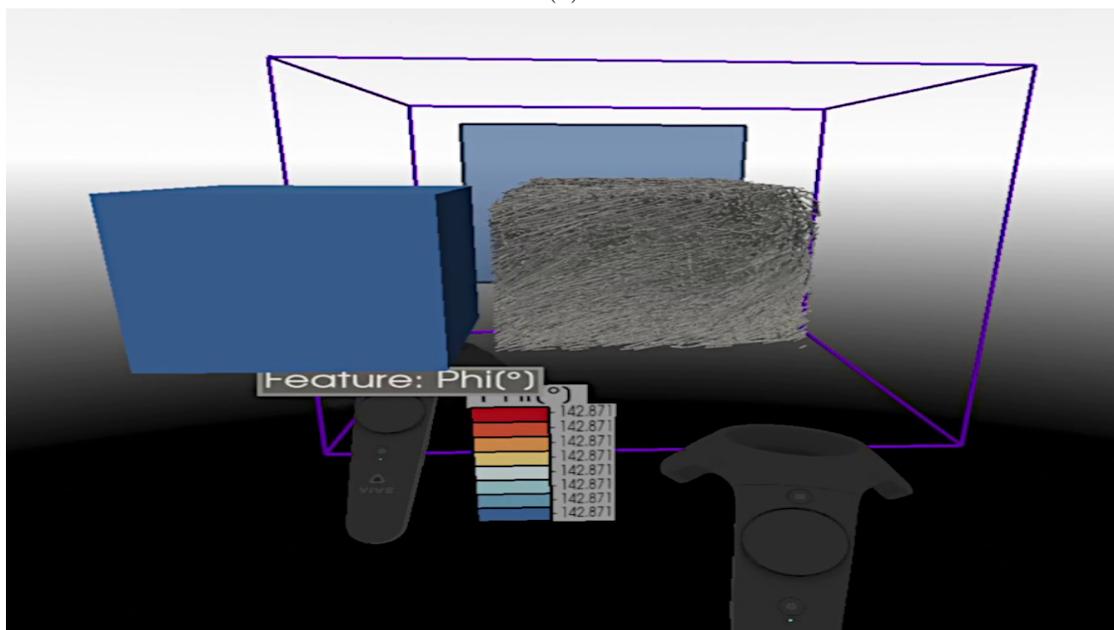


Figure 7.2: Depiction of the graphical interface for loading the data. After starting the VR module and loading the .csv file the virtual environment is loaded.

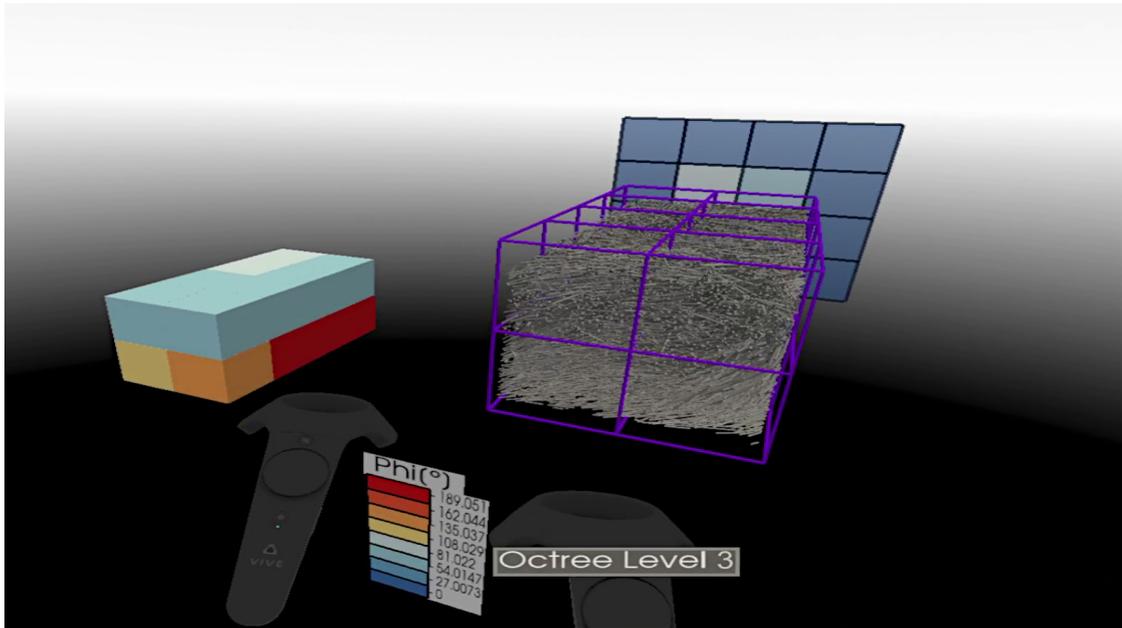


(a)

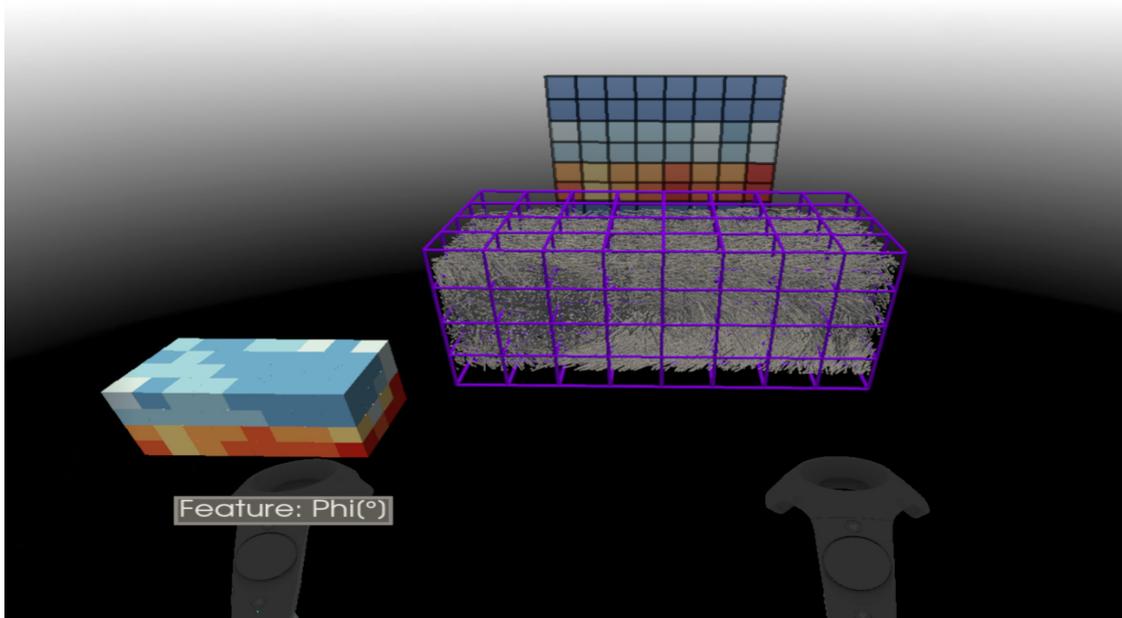


(b)

Figure 7.3: Start of the exploration after loading the dataset. (a) The user stands in front of the rendered volume, which is enclosed by an equilateral bounding box, i.e., the octree level one. (b) The user opens the MiM to get the weighted average of the currently selected fiber characteristic.



(a)

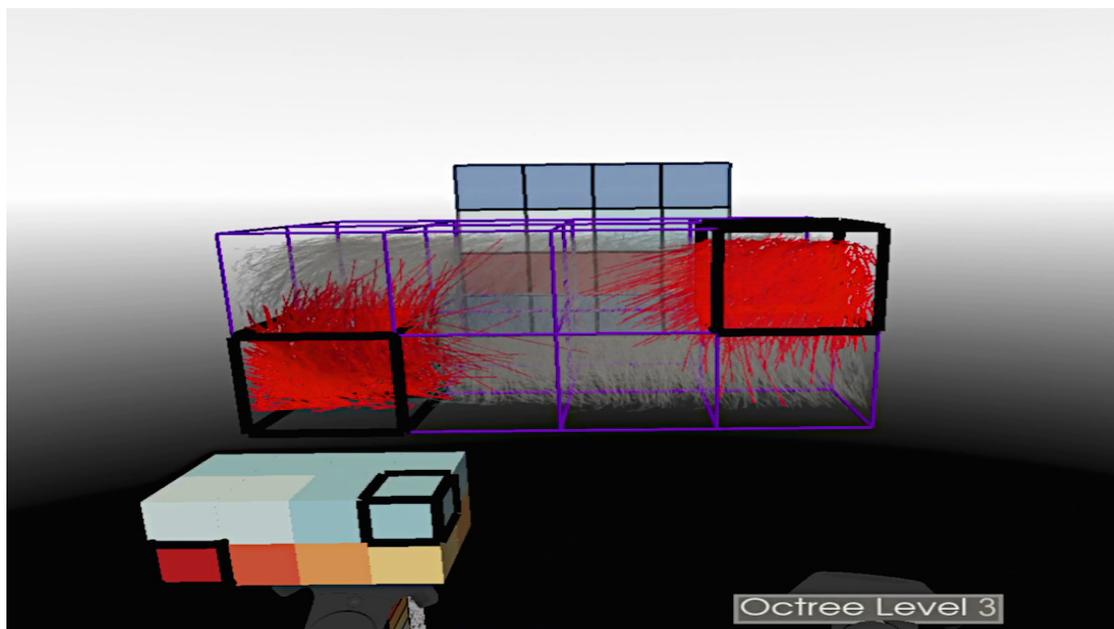


(b)

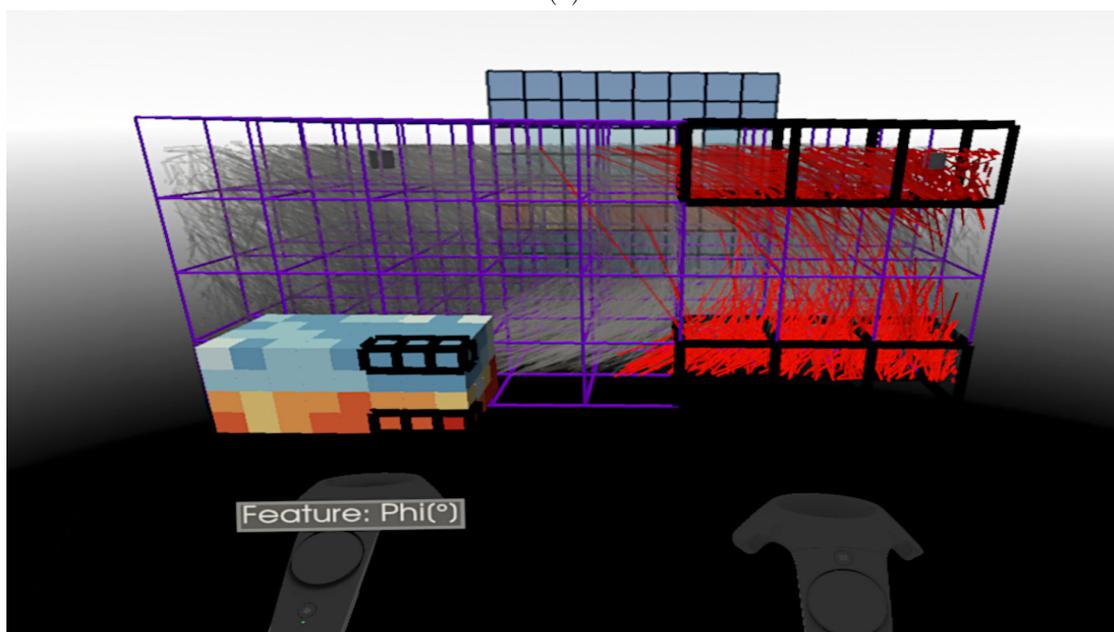
Figure 7.4: The user inspects different octree levels. (a) In octree level three, the MiM's heatmap allows the user to detect a difference in the fiber characteristic "Phi" between the upper and lower part of the volume. (b) The user switches to a higher octree level to get a more detailed view of the regions.

To better understand the explored values in their spatial context, the user has to interact with the MiM. For this purpose the differently colored areas in the MiM are picked by multi-selection. In the second level, in Figure 7.5a, the various orientations at two different locations in the volume can be easily recognized. For closer examination, the more detailed areas in the higher, third octree level are also marked. Here it is also possible to obtain precise information about the orientation of the fibers through the highlighting in red. This allows the user to view individual fibers from a well-defined area, thus further supporting his hypothesis that this fiber-reinforced material consists of two differently oriented areas. Through this examination it can be visually determined that the orientation of the fibers in the selected regions is opposite except for some very long fibers, which is confirmed by the 3D heatmap. The regions with opposite fiber orientations can be seen in Figure 7.5b.

Another possibility to get additional information about the fiber structure and to reduce clutter, are the exploded views. These allow the user to better follow the different fiber orientations between the top and bottom part. Using the eight-region technique, followed by a relative displacement, the user can take a closer look at the inside of the volume in octree level three, as shown in Figure 7.6a. This allows the user to identify interesting areas between the exploded regions. Since fibers are shifted with the region of their highest coverage and thus are not cut or broken, the user can detect relatively long fibers in the lower left part of the volume. Now, the user is interested in how these particular fibers are distributed over the regions. Therefore, the user now selects these regions on the left part of the shifted volume, as shown in Figure 7.6b, and detects an area of high similarity. The user can now see that some of these very long and similarly oriented fibers are mainly present in the left part of the volume. So, the user can determine through this cluster that these fibers have their highest coverage on the left side. Furthermore the user can recognize that some fibers of the selected region are also present on the right side of the volume. It can be determined that there is a natural boundary, where the long fibers end and new long fibers are formed. A certain layering of these fiber regions can be detected, which also has an influence on the change of orientation between the upper and lower volume region. Some of these discoveries were already known to the experts before the investigation, but could also be found easily with the developed techniques. As a result, even beginners can discover certain properties of composite materials through our tool.



(a)



(b)

Figure 7.5: More precise exploration of the individual fibers of a region through multiselection. (a) In octree level two it is possible to visually detect a varying orientation of the fibers within the two regions. (b) By switching to the third level, the area of differently orientated fibers can be determined more precisely by selecting certain regions of interest.

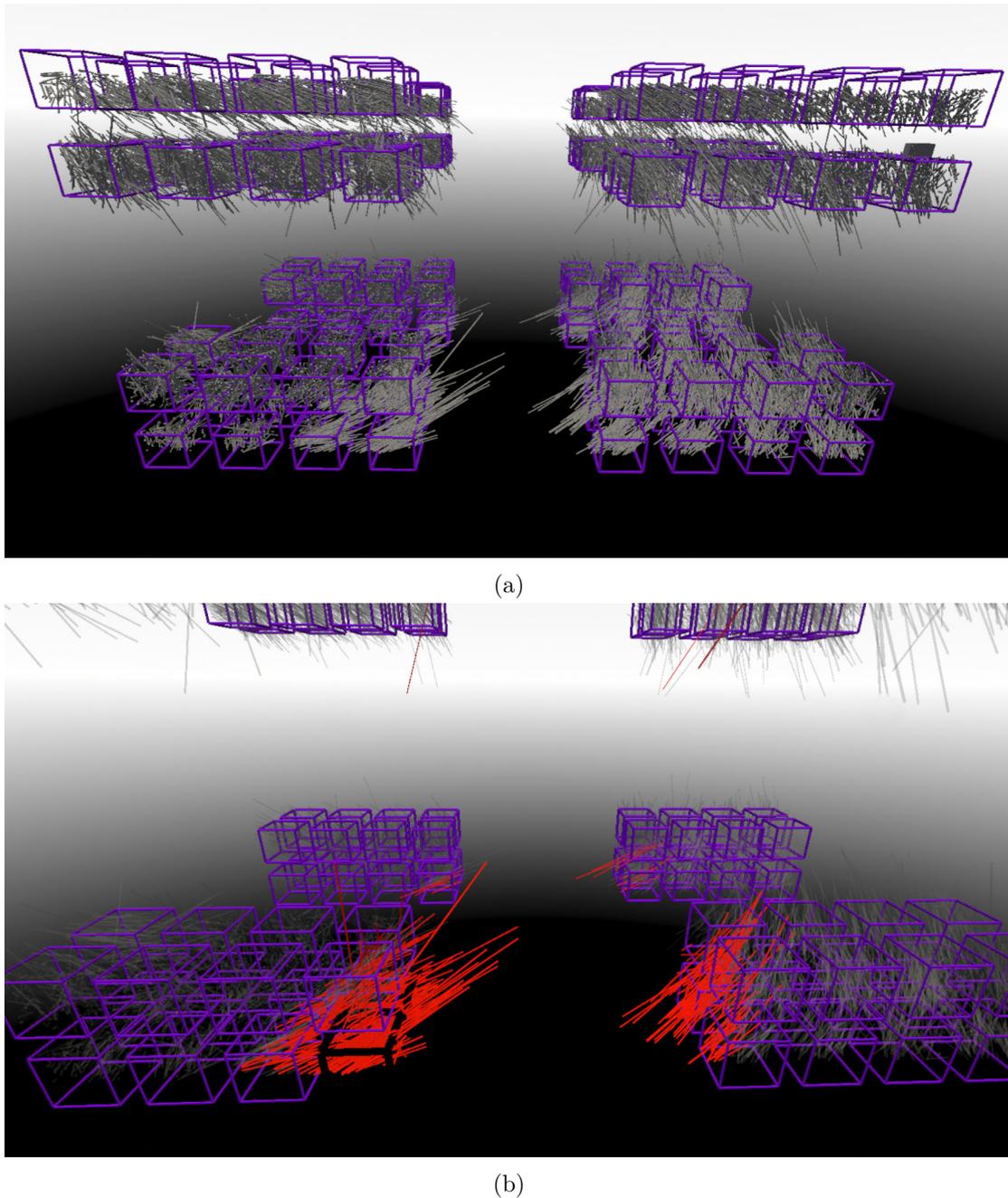
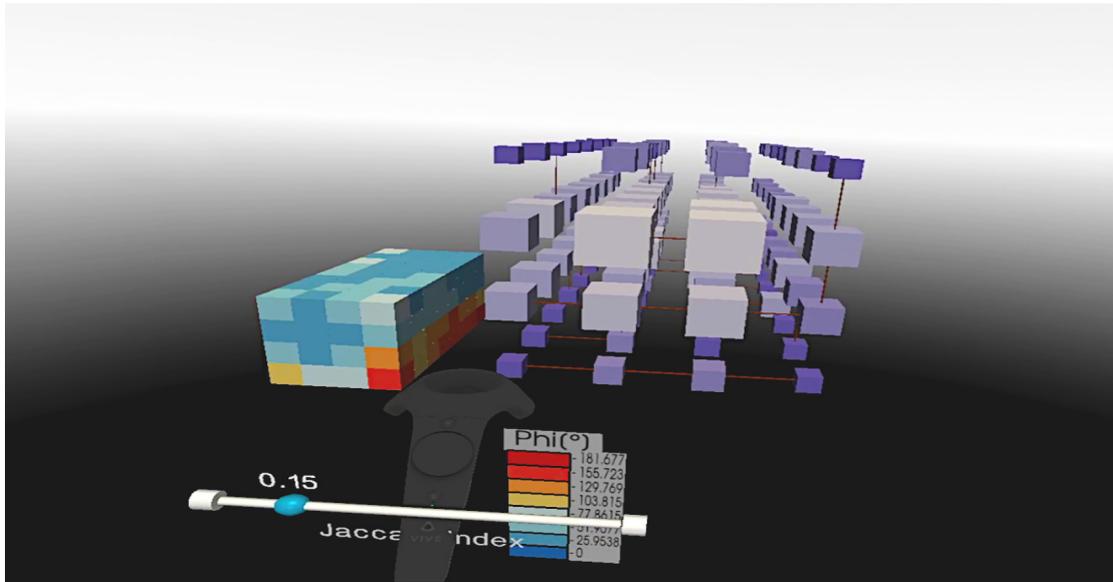
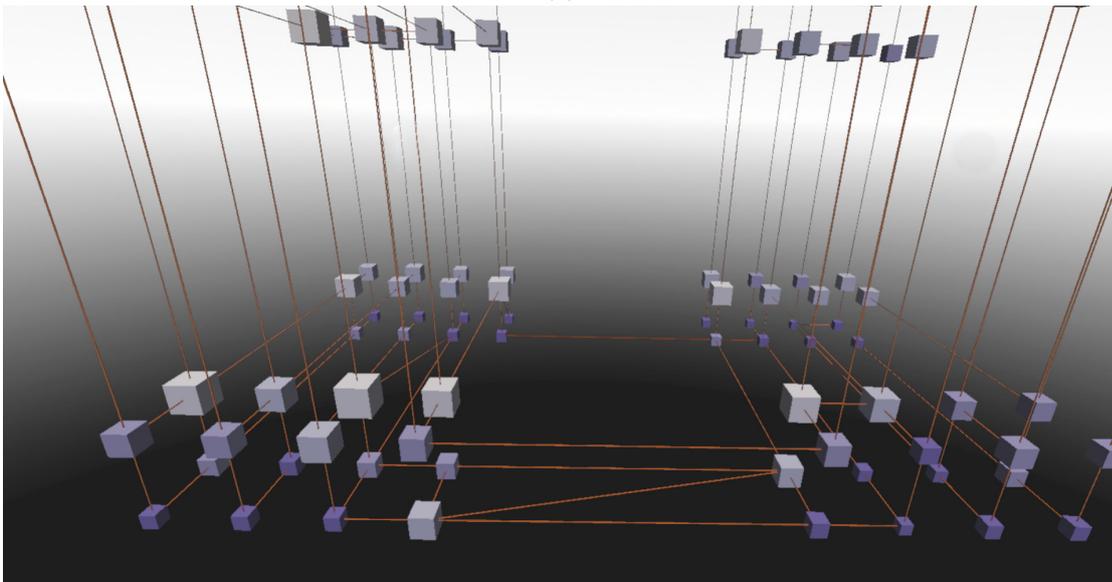


Figure 7.6: Examination of the interior of the volume by creating an exploded view. (a) The user displaces the regions through the eight-region technique as well as through a relative displacement. The clustering associated with the fiber displacement makes regions with interesting fiber properties visible. (b) To view the long fibers in the lower left area, the user marks the inner areas and can thus see in which regions of the volume the fibers have their highest coverage.

Finally, the user switches to the node-link diagram view, which is shown in Figure 7.7a. The user changes the threshold of the Jaccard index to display relationships between regions consisting of more than 15 percent of the same fiber. This can be seen by looking at the Jaccard index slider on the MiM, where the current threshold is written. To learn more about the similarity of the surrounding neighborhood, the user lowers the threshold of the Jaccard index again, which can be seen in Figure 7.7b. As a result, regions with more than 10 percent similarity are now connected by links. The user notices in this mode the previously observed highlighting, that the left region share fibers with the regions on the right side. Through the links in the diagram, the user immediately identifies that these regions share more than 10 percent of their fibers. This means that the left side and the right side are very similar due to these long fibers. It becomes evident that in the lower central part of the volume the regions share fibers horizontally. It is also visible that mostly vertical links are contained in the remaining parts of the volume. This is again an indicator of the fiber orientation in the volume, which contains more vertically than horizontally oriented fibers and therefore horizontal links are missing. Finally, the user can also estimate the number of fibers by the encoding of the cubes. Here the user can see that the previously selected regions were of different size. If regions are far apart it is more difficult for the user to estimate the size of the cubes. Therefore it is possible to confirm the change by using the different coloring of the cubes.



(a)



(b)

Figure 7.7: Inspection of the fiber distribution and the relations between the regions by switching to the node-link diagram. (a) The relationship between regions with more than 15 percent similar fiber content is shown. The fibers traversing between the regions are abstracted to a link, i.e., a line of certain thickness and color. (b) The user can decrease the threshold concerning the Jaccard index to show lower similarities and highlight the patterns found in the previous exploration steps, like the similarity of the front regions of the volume.

Finally, to examine the regions of interest more closely, the user creates a histogram. For this purpose, he selects two regions to be examined, as shown in Figure 7.8. At the first selected region a histogram visualization appears. The user then switches to the "Phi" feature by making wiping movements to view the distribution in detail. The user will notice that in the range between 0 and 17 degrees about 59 fibers are in the green region and less than 10 in the pink region, which can be seen in Figure 7.9. Bins with no fibers are displayed as 2D planes to guarantee a comparison between two pairs of bars. With this approach the user does not lose the context which pairs of bars cover the same interval, i.e., bin. 99 Fibers with 17 to 34 degrees are only available in the green region, and in the range between 256 and 359 degrees only fibers of the pink region (in the range of 10 to 50 fibers) are present. This allows the user to confirm his hypothesis that regions at the top of the volume are oriented differently than at the bottom. It is quickly possible to associate the left-leaning distribution of lower degrees with the green region and confirm the right-leaning distribution peak, of higher degrees, with the pink region. Furthermore, the 3D histogram allows the user to support this assumption by concrete numbers.

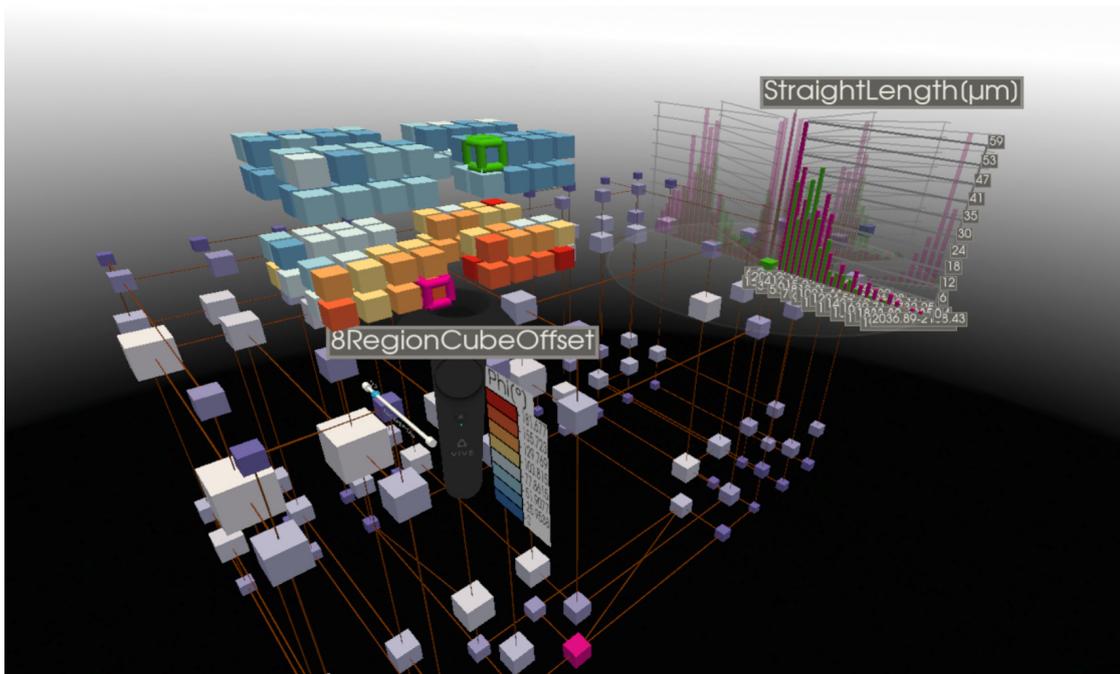


Figure 7.8: Visual comparison of the characteristics through the histogram representation. The user selects two regions, which are highlighted, and a histogram is calculated. The 3D histogram allows the user to numerically verify the distribution of the fiber characteristics.

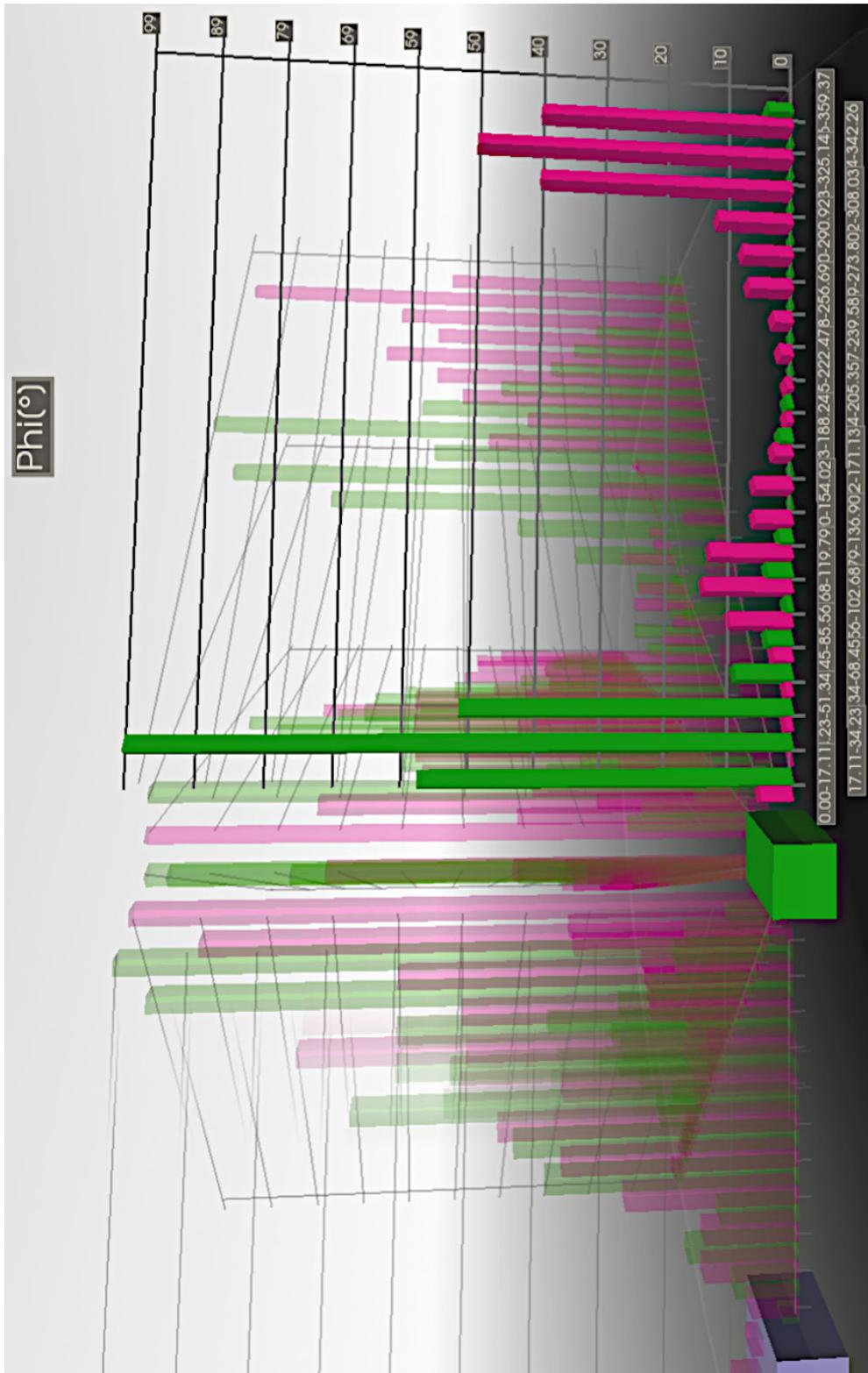


Figure 7.9: The previously discovered dissimilarities in the fiber characteristics "Phi" between the upper and lower part of the volume can be inspected through numerical values.

7.3 Evaluation

This section explains the user study process in detail. The goal was to support the immersive exploration and interaction of fiber data to gain new insights into the complex multidimensional volume data. A main focus of the study was therefore to receive first realistic insights into the usability of the framework and to enable the users to gain expected or even unexpected findings for their work in the field of fiber reinforced polymers.

7.3.1 Workflow

To test our system we rely on a qualitative user study. The focus was to evaluate whether the framework supports domain experts and novices in the exploration of fiber datasets. For this reason seven participants were asked to evaluate the system in the study. Among the participants were four female users and three male users. Furthermore, the group consisted of four domain expert, two novices in this domain, and one computer scientist from the field of visualization, who works with fiber datasets.

For the study we followed a strict procedure that started with an introduction to the application. During the first 15 minutes the participants were shown the controls and possible actions in the system. The same dataset of a glass fiber reinforced polymer with 49618 fibers was prepared for every user. Using this example, the participants were shown how to move around the 3D world, how to create and interpret the MiM and MIP, and how to use and evaluate the node-link diagram and 3D histogram.

Then a new dataset was loaded for the participants. This dataset is the one described in Section 7.2. Participants were then asked to put on the HMD and begin exploring the fiber dataset. The participants were also told that the system can be used both standing and sitting. They were asked to speak out loud what actions they currently intend to take and what conclusions they draw from the presented views. All comments and expected or unexpected results were written down. The participants explored the virtual environment for an average of 25 minutes. After the completion of the exploration, the participants were asked about their state of health and afterwards we started with a semi-structured interview.

The questions asked were based on general themes. They were divided into general questions about VR, the virtual environment, the user's well-being, as well as the MiM, the exploded view, the node-link diagram, the 3D histogram, and finally the general appeal of the spatial overview. The interview lasted about 25 minutes. The participants were asked whether they had previous knowledge of VR and how they felt in the virtual environment. It was found that except one of the participants, none of them had any previous knowledge of VR. However, all of them reported that they found the experience exciting and interesting. Moreover, none of the participants felt dizzy or nauseous after the session. Five participants even stated that they would like to use the system over a longer period of time, which we consider promising for the use in the experts' daily workflow.

After the general questions, we started with the first theme, the Model in Miniature. The participants all agreed that the idea of a scaled-down volume was very good. They all reported that it helped them to keep their orientation and also let them quickly identify interesting regions through the heatmap. The participants also said that the handling is very intuitive and that it is of great advantage that the MiM moves along with the controller, as this ensures that the MiM cannot get lost in the world. One participant reported a phenomenon that we had not expected. The participant said that the MiM felt heavy, because it looks like a massive body and the controller feels to be exhausting to use during longer operations. Another participant noted that it would be beneficial to freeze the MiM in the world for a short period of time during the selection process. The idea resulted from the fact that the participant had to keep the left controller stable enough to select accurately with the right one inside the MiM. If the user holds the controller too unstable or the controller tracking becomes inaccurate, the selection in MiM becomes difficult. This led to a further recommendation, where the MiM should be scaled larger with decreasing size of the regions to reduce wrong selections. Several participants also mentioned that the decision to make the MiM non-rotatable through controller gestures was a good decision, because they used the MiM as a reference and would otherwise have lost their orientation. The users noticed that the movement around the volume would also contribute to an increased spatial sense.

Next, we wanted to know their opinion on the exploded view, the selection in the MiM, and the volume. The overall feedback on the exploded view and the different displacement modes was very positive. The users liked the type of interaction for the selection and the exploded view very much and found it intuitive. They appreciated the ability to combine the displacements to explode the volume according to their needs. One participant said *"This [the exploded view] gives me a quick way to analyze the inside of the volume"*. Two participants felt that the relative and eight-region displacement helped them best, as these modes maintain the structure of the volume best. Furthermore, the selection was well received by all participants. The intuitive interaction and the highlighting of the fibers in the selected region in red with the rest being semi-transparent was very well appreciated. Only one of the tested persons had problems with the selection of regions in MiM. We suspect that the reason is due to the type of selection area on the controller. The virtual spot on the controller that is used for selection, is located further back on the device, so the participant did not move the controller deep enough into the volume. The ability of the exploded view, to cluster the fibers, was also found to be very useful. One user said *"This allows me to observe the fibers very well during shifting"*. One of the disadvantages mentioned was that, when multiple selections were made, all fibers from all regions were highlighted in the same color. It was noted that different colors could be used in order to identify the regions. It was also noted that the fibers of a selection could be colored, if desired, specifically concerning the requested attribute, so that the individual values of the fibers could be identified, rather than just an average value.

Afterwards the participants were asked about the node-link diagram. We found out that the benefit strongly depends on the respective knowledge of the user. Experienced users

generally did not need the diagram and could derive the information using selections and the MiM with its heatmap. Novices in the domain of fiber reinforced polymers found the representation of the number of fibers as nodes and their relationships as links helpful. Some participants thought the usability of the Jaccard index would benefit from a color legend like the one used for the 3D heatmap. The encoding of the Jaccard index was also discussed because, in the dataset used, the similarity of the regions was only visible at 20 percent. In the range between zero and 20 percent the color and thickness of the lines were not distinguishable from each other. In this case, it is recommended to adjust the encoding to the existing range of values to highlight small changes. Another idea for improvement was to limit the Jaccard index to the currently selected feature. However, the ability to show relationships was perceived as supportive and one participant said *"The Jaccard index is very useful and might be helpful to see in the volume representation"*.

Then the participants were asked about their opinion regarding the histogram. It turned out that especially experts found the visualization technique very helpful. The possibility to get exact numerical values is very important for them. Especially beginners had the opinion that the display was very precise and compact, and provided almost too much information for them. The participants also mentioned that the technique of highlighting the histogram, which they were looking at, was not essential but not disturbing either. The transparency of the remaining histograms was perceived as good. A rather regular request of the participants was to place the histogram manually. One participant even said *"I find the MiM on the controller very helpful, so I could well imagine placing the histogram there as well"*. All participants found the book metaphor very intuitive and the resulting page-turning interaction very natural.

Finally, the participants were asked about their general impressions of the three-dimensional exploration and could give any additional feedback. Some participants said that they would have preferred a way to rotate the world, because *"at the beginning you don't have the confidence to move around the volume"*. The Maximum Intensity Projection also received positive comments as it gave a quick insight into the maximum values of the fiber characteristics. Moreover, the view-dependent display of the MIP was never perceived as disturbing, but as an additional supporting visualization method. One user also suggested to implement a tutorial for new users, in which the button description is shown in the environment to make it easier to get started. The participants also said that they did not miss 2D charts, but that a coordinate system would have been helpful. The participants were further questioned how they perceive the environment. All participants, except one, replied that they did not notice the background, but that it was neither disturbing nor annoying. One domain expert pointed out that the spatial presentation is very interesting, but, due to the not very accurate rendering quality of the current hardware, no exact values can be determined. The exploration in VR is of special interest for students, novices, and customers. The expert sees the potential to show the characteristics of a dataset in a very simple and expressive way through an immersive exploration. With increasing accuracy it would also be a good extension to the current 2D workflow. A special opportunity, according to the experts, would be the

use for curved fibers, which cannot be efficiently tracked and analyzed by 2D slice views.

Overall, the feedback of the participants was very positive. Some users said the framework *"is very impressive"* and *"you can fully immerse yourself in the world"* and that one can get *"a very good feeling for the specimen"*.

7.3.2 Results

After the semi-structured interview the participants were given a questionnaire to evaluate the effectiveness of the chosen visualization techniques. The participants all discovered the different orientations in the volume as presented in Section 7.2. The questionnaire was therefore designed to clarify how well the implemented visualizations and interactions contributed to achieve these insights. The questions were designed according to a Likert Scale, where users could rate each question through a range from "Strongly Agree" to "Strongly Disagree". The five point scale was applied to 12 questions, covering the range of implemented features. The questions are grouped into five topics based on the implemented techniques and listed in Table 7.1.

Model in Miniature (MiM)

The MiM can support the navigation/orientation in the environment.

The MiM can be used to discover similar/dissimilar feature distributions in the regions.

Setting the octree level supported switching between overview and more in-depth view.

Exploded View (EV)

The EV can improve the usability of the MiM.

The EV can increase the overview on the volume.

The different displacement modes of the EV can support the exploration.

Node-Link Diagram (NL)

The presentation as nodes can support the overview of the fiber content.

The visualization of the neighbourhood relations through links can supported the exploration.

Histogram

The comparison of two regions through the histogram can support the exploration.

The focus and context visualization as book metaphor can improve the usability of the histogram.

Overview

The spatial representation can facilitate the exploration of fibers.

The Maximum Intensity Projection can be a good visual support for the exploration.

Table 7.1: Questions for the evaluation of the implemented visualizations. The individual questions of the questionnaire are divided into the five topics, written in bold, derived from the methods used in the framework.

The results of the evaluation can be seen in the chart in Figure 7.10. Each of the seven participants answered each question. In the results of the evaluation the distribution of

the rating can be seen as percentages and the average value is marked in the grey circle. The best possible value is 5 (Strongly Agree) and 1 (Strongly Disagree) is the worst. The bars show what percentage of participants have rated a specific question. The grey circles therefore indicate the average ranking (1-5) for this question. As can be seen, all the techniques performed very well and the worst score was not assigned. In order to better compare the individual techniques, the questions were summarized and evaluated according to the main topics shown in Table 7.1. For this purpose, the individual rankings of the questions were summarized and presented as the overall result of the respective topic. Therefore each topic consists of more than seven answers, depending on the number of questions asked per topic. For example, in the topic *Model in Miniature (MiM)*, the percentage refers to 21 answers (seven answers for each of the three questions). The results of the ranked methods can be seen in Figure 7.11.



Figure 7.10: Evaluation results of the questionnaire. Each question was evaluated along a Likert Scale with possible scores between 5 (Strongly Agree) and 1 (Strongly Disagree). The grey circle depicts the average score of the question.

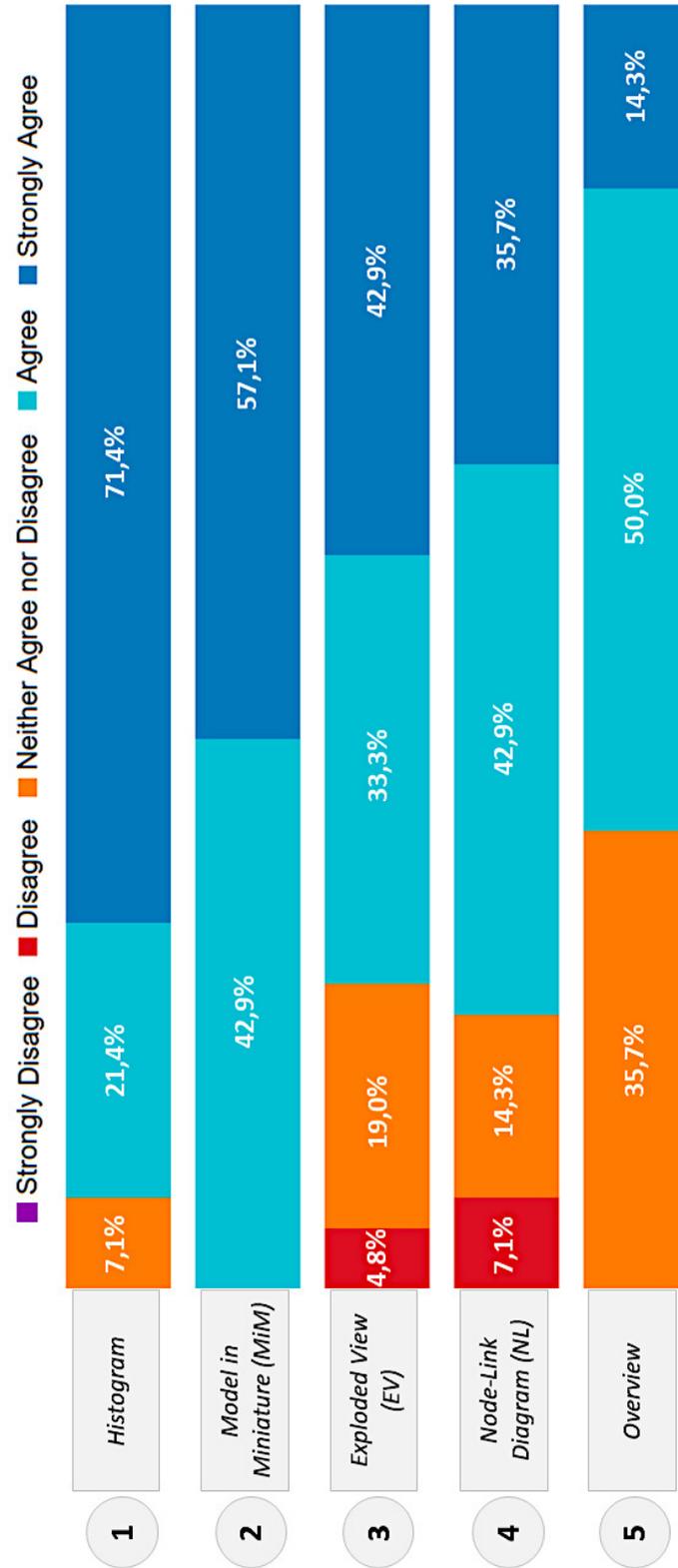


Figure 7.11: For better evaluation, the scores were arranged by topic to rate the individual methods. A topic consists of all included questions, and shows the summed scores as a result.

The results give us valuable insight into the usefulness of certain IA methods for fiber analysis. Answers with a score of 4 or 5 are considered a positive result, 3 is a neutral result and the rest means for us that the technology needs improvement. The most important one is the ability to perform a numerical analysis, which is very important for domain experts and is very well covered by the 3D histogram. All 7 participants found the possibility to compare two volumes necessary for exploration. Overall, the topic histogram was rated positive with 13 of 14 answers. Our new visualization and interaction technique, the MiM, is ranked second, which shows that this innovative approach was well received by analysts in the material domain, since it was rated positive by all participants. It is also evident that every feature of the MiM was considered equally important for exploration. In third place is the exploded view. The Topic was rated positive by 16 out of 21 answers. The various displacements that have been developed were positively evaluated by 5 out of 7 participants. The explosion of the volume was perceived by all participants as an important support for the exploration process. Only the explosion of the MiM needs to be further improved, as described in Subsection 7.3.1. The Node-Link diagram is in the second but last place, which is due to the fact that the representation of the fiber count in regions was not necessary for experts. However, the possibility to analyze relationships between neighbors was positively received by 5 out of 7 participants. Finally, at the last place is the topic Overview. Here the MIP was unusual for many participants and was therefore only positively rated by five out of seven participants. However, the general exploration of fibers in immersive environments was rated positively by six participants. Further research is therefore needed to improve the use of three-dimensional representations and to develop more tools for detailed investigations.



Conclusions & Future Work

This last chapter concludes the thesis with its most important cornerstones and the possible work for the future. We summarize the research findings and discuss possible improvements found through the evaluation.

8.1 Summary

The goal of this thesis was to develop a framework for the immersive analysis of multidimensional volumetric data. Particularly the objective was to support researchers and experts in the field of material science. Especially in the field of analysis and development of fiber reinforced composites, data representations are required to support the users in their cumbersome cognitive tasks. To reflect the inherent spatial structure of complex, heterogeneous material systems from NDT data and to make the material's high-dimensional data spaces comprehensible, we developed techniques in the current research field of Immersive Analytics. Immersive technologies such as Virtual Reality offer new and unexpected opportunities to present data and provide new perspectives for their exploration. Since there are only few well-established guidelines for working in an immersive workspace and for the adaptation of existing visualizations methods or the development of new visualization techniques for the new modalities (e.g., VR, AR), research is even more challenging. We have formulated seven research questions that address the new opportunities for immersive representing and interacting with data.

***Question (Q1):** How should an immersive workspace be structured to support the exploration of fiber reinforced composites?*

With question Q1 we wanted to find out how the environment for the exploration of fiber datasets should be designed. In doing so, we decided to follow the "Limit to the essentials" concept. The domain experts want to focus only on the essential information, which for their analysis is the volume. The interview confirmed the hypothesis that less

is more and that the space should primarily show the volume with its fibers to facilitate an unobstructed exploration.

Question (Q2): *Is it possible to enable the immersive exploration of fiber-reinforced composites utilizing only 3D spatial representations?*

Question Q2 enhances the concept of the immersive workspace by avoiding 2D representations that are not required. In this way, we want to exploit the full potential of the immersive world for the analyst's workflow. It is not important to us to continue the debate about 2D versus 3D effectiveness, but to demonstrate that with the use of 3D visualization methods, the comprehension and use of the visualizations can be simplified. During the development process, we emphasized the spatial features of the data and enhanced them with abstract information. The positive effect of an immersive workspace that avoids 2D representations can be seen in the results of the evaluation. Many participants told us that the framework, we have developed, would be very helpful for students, novices, and customers to introduce them to the complex characteristics of fiber datasets. Here, the spatial representation contributes to the recognition of patterns and unique features through the user's visual cognitive abilities.

Question (Q3): *Which visualization and interaction idoms support natural exploration in the immersive environment?*

This question refers to the final realization by appropriate interaction and visualization techniques. Concepts like "Versatility", "Avoiding control components", "Making manual mode switching unnecessary", and "Ready-to-use tools" are applied in combination. The goal was to make the interaction as natural and intuitive as possible. For this reason the MiM is the most essential tool in the application. It enables a quick overview of the volume, it allows to keep the orientation in space, and can be used to localize distributions in space. It is always ready to use and positioned at the controller, but never hides important areas since it can be closed anytime. As can be seen in the evaluation, this technique was the second most important function in the framework and was only displaced by the possibility to retrieve detailed values. The histogram in its book form also reflects the reality through specific movement sequences. Due to the interaction of flipping through the pages, a physically correct and natural handling is possible, which was found very beneficial by the users. The absence of menu items and mode switching allows the analyst to interact seamlessly within his workflow. This is reflected by the selection, which is possible at any time through an interaction with the regions in the MiM or the volume.

Question (Q4): *Which interactions and visualization methods facilitate an overall view of the volume and a reduction of clutter?*

Question Q4 also deals with facilitating a fluid exploration. The goal was to give the user the possibility to get an overview of the volume at any time and to increase the overview by reducing clutter if necessary. One way to give the user an overview was to display a maximum intensity projection. This technique enables the user to get a quick the overall view and is only shown in the viewing direction, which prevents additional clutter in the

environment. This way the user can see the most important distribution values while still having a view of the fibers. Another technique to achieve this effect is the exploded view. Here the user can move the MiM and the volume apart at any time to get a view of the inside. However, the entire structure is always retained and an overall view with less clutter is achieved. The necessity for this technique and its benefits can be judged from the rating given by the participants in the evaluation. Here we could see that the explosion in the volume was well appreciated, but that the explosion for the MiM still needs to be revised in order to use its full potential.

Question (Q5): *How can spatial regions with similar fiber characteristics be identified in the immersive environment?*

This question deals with the information required by domain experts. Of great interest to them is the spatial distribution of fiber characteristics in the different subregions [WAL⁺14]. In this framework, we have therefore divided the volume using an octree data structure. With each level, the partitioning becomes finer and patterns can be found by displaying the characteristics as a 3D heatmap on the MiM. This makes the spatial distribution quickly visible in the MiM and the user has the possibility to view the regions by moving around or into them. Fiber attributes in the interior of the volume can also be examined more closely through an explosion of the volume, which, according to the evaluation results, was frequently used.

Question (Q6): *How can similarities between the spatial subvolumes be revealed?*

Question Q6 deals with the spatial arrangement of the regions. The developed node-link diagram should provide the expert with the necessary overview of the fiber content and the relations of the regions to each other. Through the evaluation we found out that the fiber contents can be determined by experts faster through other representations. The visualization of relations between regions can be beneficial for experts, but it is not fully used in its current design and needs to be revised. It is also important to note that node-link diagrams are not among the standard visualizations in the field of fiber analysis and therefore a certain degree of familiarization is necessary. The spatial representation of such a diagram was received positively.

Question (Q7): *How can a detailed comparison of fiber characteristics between subvolumes be shown?*

Question Q7 again refers to a requirement of the experts. They expressed the need to be able to read numerical values of fiber characteristics. The reason for this is that in the currently used applications the experts primarily derive their hypotheses from numerical values. To satisfy this demand and still retain the three-dimensional representation, a histogram was chosen as focus and context visualization technique, which appears after selecting two regions. To reduce perspective distortion and to make the interaction more natural, the book metaphor was chosen. To avoid disorder, only one histogram is displayed in the viewing direction to maintain the overall context, and keep the focus on the individual values of the currently viewed attribute. The users were all very satisfied

with the visualization, which is also reflected in the evaluation, ranking the 3D histogram in first place.

The research questions and techniques described here can be applied to other domains. Since the main focus has been put on the development of new visualization and interaction techniques for an immersive exploration, these methods can also be useful for other types of data. In the field of materials science these could be pores in composites or sponges, but also XCT images of food can benefit from these virtual explorations. The use of medical data such as scans of blood vessels, tumors, or thrombi can be of great benefit in medical areas. The techniques developed here can be used for various purposes. It is therefore of interest to adapt the system developed here to the specific needs of the respective experts in order to generalize the system further.

We presented an immersive virtual reality system for the visual analysis of characteristics in fiber reinforced polymers. We have successfully applied the latest discoveries of the Immersive Analytics field to the techniques of material analysis. The overall positive feedback from the users provided important information about the strengths and weaknesses of our application. This thesis has taken a step towards the further development of future immersive analysis platforms.

8.2 Limitations & Future Work

Considering the described research questions and the evaluation results, some of the strengths and weaknesses of our application can already be identified. Our tool offers a good overview and detailed views into the volume, but for experts more numerical values have to be displayed. It is also of interest to select single fibers and get exact characteristics about them. Another disadvantage is the effort of such an exploration. At the moment the VR HMDs are still quite heavy and connected with many cables. The experts usually do not have the time between their XCT scans to put the VR device on and off as a numerical value of a characteristic is usually sufficient for them to decide about the specimen. A further problem arises from the currently available computing power. With more than 200,000 fibers, functions like the exploded view are no longer in the range of 90 frames per second (FPS). This results in uncomfortable waiting times or delayed displays that can disturb the exploration. Some of these problems can hopefully be resolved by future hardware.

There is also potential for improvement for future applications. A further development of the application could consider using the voxel data of the volume. This would allow the exploration of curved fibers, which is not possible with conventional 2D images of cross sections. An extension to pores or similar features is also possible. Finally, it is necessary to consider how to match exact numerical data with current 3D renderings and show them effectively to the user in the immersive environment.

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