

ImNDT: Immersive Workspace for the Analysis of Multidimensional Material Data From Non-Destructive Testing

Alexander Gall
University of Applied Sciences Upper
Austria
Wels, Austria
TU Wien
Vienna, Austria
Alexander.Gall@fh-wels.at

Eduard Gröller
TU Wien
Vienna, Austria
VRVis
Vienna, Austria
groeller@cg.tuwien.ac.at

Christoph Heinzl
University of Applied Sciences Upper
Austria
Wels, Austria
Christoph.Heinzl@fh-wels.at

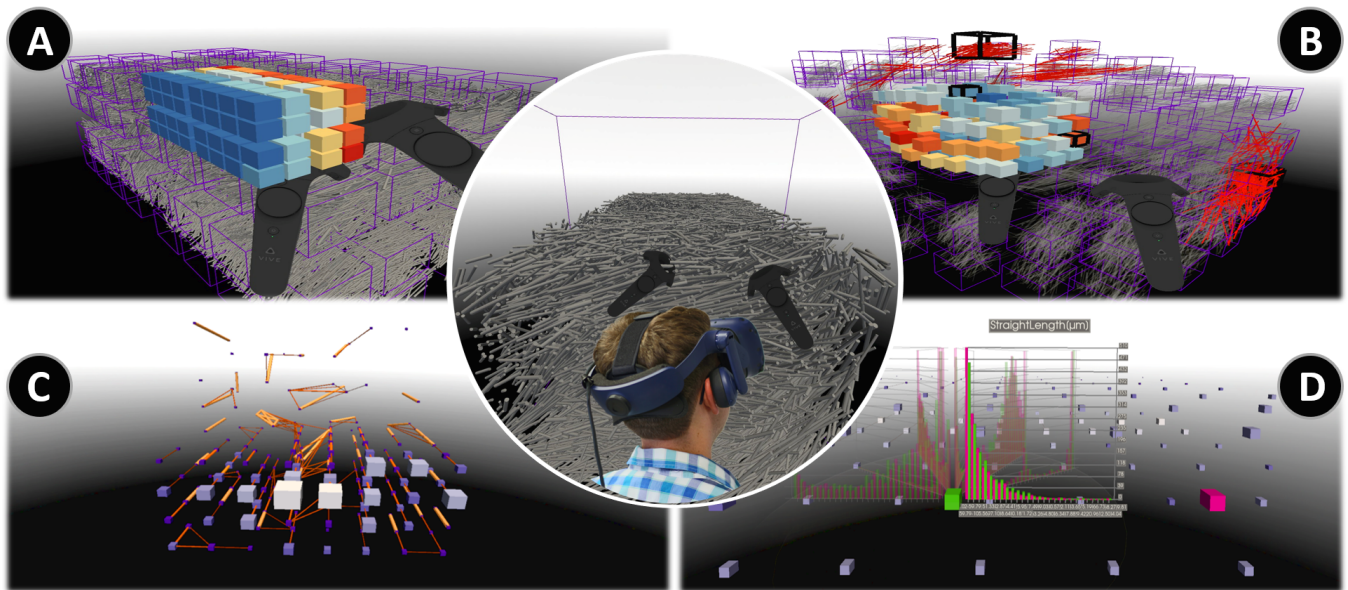


Figure 1: ImNDT's immersive workspace, where analysis of material data is enabled by the abstract model in miniature (A), selections and exploded views (B), relationships in a similarity network (C), and comparisons in our 3D histo-book (D).

ABSTRACT

An analysis of large multidimensional volumetric data as generated by non-destructive testing (NDT) techniques, e.g., X-ray computed tomography (XCT), can hardly be evaluated using standard 2D visualization techniques on desktop monitors. The analysis of fiber-reinforced polymers (FRPs) is currently a time-consuming and cognitively demanding task, as FRPs have a complex spatial structure, consisting of several hundred thousand fibers, each having more than twenty different extracted features. This paper presents ImNDT, a novel visualization system, which offers material experts an immersive exploration of multidimensional secondary data of

FRPs. Our system is based on a virtual reality (VR) head-mounted device (HMD) to enable fluid and natural explorations through embodied navigation, the avoidance of menus, and manual mode switching. We developed immersive visualization and interaction methods tailored to the characterization of FRPs, such as a Model in Miniature, a similarity network, and a histo-book. An evaluation of our techniques with domain experts showed advantages in discovering structural patterns and similarities. Especially novices can strongly benefit from our intuitive representation and spatial rendering.

CCS CONCEPTS

• Human-centered computing → Visualization; Interaction design;

KEYWORDS

Multidimensional data visualization, immersive analytics, virtual reality, interaction techniques, fibre-reinforced polymers

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

VRST '21, December 8–10, 2021, Osaka, Japan

© 2021 Association for Computing Machinery.

ACM ISBN 978-1-4503-9092-7/21/12...\$15.00

<https://doi.org/10.1145/3489849.3489851>

ACM Reference Format:

Alexander Gall, Eduard Gröller, and Christoph Heinzl. 2021. ImNDT: Immersive Workspace for the Analysis of Multidimensional Material Data From Non-Destructive Testing. In *27th ACM Symposium on Virtual Reality Software and Technology (VRST '21), December 8–10, 2021, Osaka, Japan*. ACM, New York, NY, USA, 11 pages. <https://doi.org/10.1145/3489849.3489851>

1 INTRODUCTION

In the field of materials science extensive investigations are essential to ensure the increasing demands on materials and components in industrial applications. For these highly complex and cognitively demanding tasks visualization systems are crucial. Application areas such as the automotive, aeronautics, medicine, but also leisure industries rely on fiber-reinforced polymers (FRPs), which are characterized by a very high strength-to-weight ratio [36]. In addition to the basic elements such as fibers and the matrix/fillers, FRPs also contain production-induced features such as pores, inclusions, or voids. The entirety of these features determines the properties and, finally, the application scenario of the respective material system. The goal is to develop new materials tailored to respective requirements by analyzing and understanding complex materials, and thus staying ahead in the competition [21, 22].

Non-destructive testing (NDT) provides the possibility to acquire data through various imaging techniques that are essential for material characterization, quality control, and metrology [24]. Advanced imaging techniques such as X-ray computed tomography (XCT) are currently being used to precisely examine fiber composite materials, that must not or cannot be damaged during the examination. In addition to 2D images, the generated NDT testing data includes large volumetric models (i.e., primary data) and high-dimensional data based on the individual characteristics derived from them (i.e., secondary data; in the case of fibers derived characteristics such as length, diameter, start/endpoint, fiber volume etc.) [1, 3, 47]. Often, such complex dataset ensembles cannot be thoroughly evaluated on conventional desktop monitors using standard 2D visualization techniques, or only to a limited extent [34, Chapter 1]. The material experts need to understand the spatial arrangement of the volume to better comprehend the overall structure of the fibers present, the distribution of the fibers throughout the volume, as well as the individual characteristics of the fibers. The number of fibers plays an important role in this context as typical samples contain from a few thousands to hundreds of thousands of fibers, each with more than twenty different extracted characteristics.

In order to render the high-dimensional data spaces of secondary NDT data in a comprehensible way as well as to reflect on and understand the inherent spatial structure of these highly complex, heterogeneous material systems, novel techniques in immersive analytics (IA) are required. Many recent studies have shown the positive effects of IA on a wide range of applications [6, 34]. Leveraging immersive data analysis techniques using technologies such as virtual reality (VR) resulted in higher levels of engagement [15], accuracy [29], and more intuitive navigation [48]. That allows users new perspectives, which were previously impossible through conventional 2D desktop applications [41, 49] and, enables better orientation and memorability capabilities [30], as well as novel immersive visualization and interaction techniques [33, 46]. By exploiting the

3D space to analyze high-dimensional datasets, using the environment as an immersive workspace [14], and by applying metaphors based on real-world structures [25], a new form of material analysis can be developed that goes beyond conventional visual analytics approaches. Specifically our main contributions are:

- ImNDT, a novel approach for the immersive exploration of secondary NDT data as generated from FRPs using VR head-mounted displays (HMD).
- Novel visual metaphors and interaction techniques tailored to the interactive analysis of secondary NDT data of advanced composites, which were developed in close collaboration with material specialists.
- A qualitative case study with domain experts and novices analyzing FRP data, in order to evaluate both usability and potential of the framework for exploring multidimensional fiber datasets.

2 RELATED WORK

Most of the related work in the domain of IA for multidimensional data is found in frameworks for information visualization, which display multidimensional datasets via three-dimensional bar charts, scatter plots, polar plots, parallel coordinate charts, and other techniques. Systems, that augment inherently spatial structures with corresponding multidimensional information, are far less common [34, Chapter 2]. In materials science, the visual analysis applications we found, primarily rely on 2D charts and offer little to no exploration in the rendering of three-dimensional volumes. The industrial applications that use immersive analysis are mainly related to training simulations and assembly instructions [50]. Currently, there are very few IA applications that aid experts in their material characterization and inspection processes.

2.1 Visual Analytics

Traditional visual analysis approaches are the most common form of material characterisation and provide accurate results that allow analysts to interpret multidimensional fiber data.

Open source system like Paraview [28], Quantify [40], and open_ia [18] enable users to visually analyse and process volumetric datasets. For this purpose, statistical calculations may be performed and displayed using different 2D charts. The current workflow is primarily designed for numerical evaluations and the actual 3D volume is usually displayed in a small view for orientation. Proprietary applications such as VGSTUDIO MAX from Volume Graphics [45] or Avizo from Thermo Fisher Scientific [43] are examples of tools that are mainly used by experts, especially in the domain of FRP data analysis. These systems also provide a reduced 3D representation of the volume, and focus on several 2D sectional views and calculated numerical values from secondary NDT data.

2.2 Immersive Analytics

Research in IA created many new opportunities for data visualization and analysis. Some of these new approaches, like spatially situated data visualisation and immersive interaction techniques, are discussed in recent surveys [13, 16]. The research presented in

these papers focuses primarily on the immersive analysis of multi-dimensional data, especially from volumetric objects.

The earlier attempts to explore the effects of immersive visualization on volumetric data were performed with the CAVE Automatic Virtual Environment (CAVE) system [10]. Schulze-Döbold et al. [39] showed the usability of the COVISE system on human X-ray computed tomography (CT) data. A study by Laha et al. [32] used micro CT datasets and found a number of positive effects from the immersive analysis, especially regarding the search of visually and spatially complex features. Both applications offer only basic navigation methods, clipping planes, and adjustments to transfer functions. Furthermore, CAVEs can only be used in a stationary setting and are more difficult to utilize due to their size and high costs. Another study by Laha et al. [31], tested the effects on task performance based on interactions used with CT datasets. The results show that 3D interaction techniques lead to an improvement over standard 2D techniques when manipulating volumes. The work of Jackson et al. [26] deals with the effects of 3D interactions in the analysis of fiber structures. They use a cylindrical, tangible object to filter the orientation of the fibers and visualize the dataset on a 3D TV display. The results show a more effective and engaged interaction with the volume through a spatial interface. A recent study by Wang et al. [46] deals with natural interactions through hand gestures in an immersive environment. The goal is to create a "What You See is What You Get" (WYSIWYG) pipeline, in which fluid interactions can be used to control the optical properties of the volume. The interactions used in these applications focus only on the volume but do not offer the possibility to interact with additional secondary data. Drouhard et al. [12] address the virtual representation of data from materials science by using an HMD to explore large crystal structures modeled with Blender [17]. Although the system provides a good overview of the data, it does not offer the possibility to utilize the immersive space or to display additional information about the structure. FiberClay by Hurter et al. [23] enables the visualization of multidimensional data of complex 3D aircraft trajectories and fiber tracks from diffusion tensor imaging (DTI) of the human brain in a virtual environment. These large, inherently spatial datasets can be explored interactively by enhancing the data with abstract information. Through tailored 3D interactions, like bi-manual selection with a ray and modification of the data mapping through motion, the geometries and data properties of the trajectories can be analyzed. A qualitative user feedback, revealed that the immersive environment together with the user's ability to change perspective, helps to discover patterns that would otherwise be difficult to perceive. For complex volumes, as fiber datasets, the used representation is not sufficient due to the low visual quality of the HMDs.

The majority of IA applications do not use volumetric, but multidimensional datasets without inherent spatial structure. These systems often obtain their spatial component by placing the data relative to each other in the three-dimensional workspace. An example of an application that uses the relative position in space for the analysis of multivariate abstract data is ImAxes by Cordeil et al. [9]. The individual attributes are displayed on a single axis in the form

of a histogram. By grabbing and placing this axis in the virtual environment in different layouts, 3D charts like scatterplots, scatterplot matrices, or parallel coordinate plots are created using a specific grammar. The type and layout of the visualization widgets (2D, 2.5D, and 3D) are more flexible than in traditional WIMP (Windows, Icons, Menus, and Pointers) interfaces and enable a highly fluid interaction through the embodied axis metaphor. 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. [2]. Since ImAxes only works with abstract multivariate data, this system cannot be applied to spatial high-dimensional fiber datasets. The Immersive Analytics Toolkit (IATK) by Cordeil et al. [8] is another application, which visualizes multivariate abstract data in a virtual environment. In this framework based on Unity [44], with an editor the user can create different information visualization widgets such as scatter plots, line plots, bar charts, and combinations of them. The possible database refers to abstract data without spatial information and the settings have to be configured in the 2D desktop environment. Since IATK requires switching back and forth between the desktop application and the immersive environment, which would disturb the material scientists in their exploration, and is merely capable to visualize multivariate data, this framework is inadequate to use for the analysis of FRPs. Hayatpur et al. [20] showed the exploration of multivariate abstract data in an immersive workspace. The data can be filtered and arranged according to the user's preference in the environment. This allows the user to spatially layout their own workflow and see it reduced in size on one's own wrist. In this application, the coordinates of the geographic data are not used for the arrangement in space and only the positions set by the user have meaning, which is why the fiber datasets cannot be visualized with this system.

Current approaches focus heavily on two-dimensional graphs or extensions of these graphs to 3D, which primarily represent numerical values. Less focus is directed at extending spatial representation with abstract information in immersive environments. To our knowledge, we present the first research in the field of immersive visualization and interaction of multidimensional NDT data.

3 ImNDT: DESIGN AND DESCRIPTION

In this section, we describe the relevant system design (see Figure 1) as well as the visualization and interaction techniques developed with the following considerations in mind.

3.1 Design Considerations

In order to support an intuitive immersive exploration of the high-dimensional spatial data, several design considerations were identified using the *Where-What-Who-Why-How* framework as presented by Marriott et al. [34, Chapter 9]. The considerations are described in more detail in the following paragraphs and are summarized in Table 1.

To facilitate the exploration of arbitrary high-dimensional spatial data, the system must be able to handle both small and large datasets. Therefore, the environment and the visualization methods have to be chosen carefully to allow for smooth and interactive use and rendering (D1). In three-dimensional workspaces, the utilization

of standard WIMP techniques does not work efficiently. Therefore, we avoid 2D GUI components, such as menus or billboards, to provide a natural interaction via controller actions. To increase immersion and the feeling of presence, we switch automatically between different modes based on the specific situation and the displayed visualization (D2). Since an important part of the analysis of FRPs is to find new hypotheses regarding fiber characteristics, as well as to verify or falsify existing ones, it is essential to offer the user different visualization techniques to highlight important aspects of the data (D3). In order to avoid the interruption of this discovery process by switching between 2D and 3D representations, three-dimensional representations are preferred (D4). Embodied interaction offers many advantages in immersive analysis. However, since the typical work environment takes place in a seated position, the navigation in the data needs to be easy to perform from this posture (D5). To support prolonged use of the application and to achieve an engaging effect, respective tools have to be simple and easy to use. The visualization and interaction techniques developed should be available any time and displayed within arm's reach (D6). To focus on the exploration of the fiber dataset and to keep the complexity low, only one primary representation is used at a time. The user therefore mainly interacts with the fiber dataset and a supporting tool without covering the environment with extra visualizations (D7).

Table 1: Design Considerations used for the visualization and interaction techniques

| | |
|----|--|
| D1 | Allow for Scalability |
| D2 | Avoid control components and manual mode switching |
| D3 | Offer Versatility |
| D4 | Avoid unjustified 2D representations |
| D5 | Facilitate office work |
| D6 | Provide Ready-to-use tools |
| D7 | Limit to the essentials |

3.2 Preprocessing

ImNDT targets secondary NDT data in the form of a *.csv file, which is extracted from XCT scans of FRPs. The fiber characterization pipeline for creating the secondary data is based on the FiberScout module by Weissenböck et al. [47], which is available as a module of the open_iA software [18]. Our tool uses the secondary NDT data to visualize the fibers through a model-based surface representation. As models cylinders are used, which support finding specific patterns more easily than in cluttered voxel based representations. In addition they also reduce the GPU power required to ensure a smooth exploration. The cylinders are rendered at the specific positions with respective lengths and diameters as stored in the dataset. This 3D representation will be called throughout the paper as fiber model (FM).

3.3 Visualization and Interactions Techniques

The goal of ImNDT is to create an immersive workspace, in which a natural exploration of fiber datasets can take place and users can leverage their own spatial cognition skills. The spatial immersion is

intended to raise the user's interest even without prior hypotheses, thus making it possible to gain knowledge from their own curiosity [34, Chapter 1][6]. In ImNDT, the user starts in a large virtual workspace with the fiber model (FM) prominently placed in the center of the otherwise empty environment (D7). The background of the environment is depicted with a color gradient, which transitions from black to white at the approximate horizon. This was chosen during development in response to user feedback, since we found out that a pure white or black environment was perceived as too bright or oppressive. We also discovered that environments without a horizon left the user with the feeling of floating while working. The user can navigate through the environment by embodied interaction and view the FM from different distances and angles. To facilitate the daily work of the experts in the office, a seated navigation is possible. Controller gestures enable the user to zoom in and out of the data, and move themselves or the FM in the workspace (D5).

In order to allow for an exploration of specific regions in the dataset, the FM is subdivided using an octree structure. This iterative subdivision into eight equally sized subregions provides the ability to analyze specific regions of interest in detail. The regions are subdivided into smaller subregions as long as one of the eight resulting subregions still contains fibers. In a pre-processing step, the percentage of fiber coverage of each fiber contained in every region is calculated. The fiber coverage is calculated from the ratio of the length of each fiber in the respective region to its total length. Fibers lying completely in one region receive one hundred percent coverage, while the coverages of fibers lying only partially inside a region are reduced accordingly. For this purpose, an intersection calculation is performed for each fiber (using start and end points) against each octree region. The individual fiber coverage is then used in subsequent visualization and interaction techniques.

3.3.1 Model in Miniature. As an overview and for intuitive navigation in the full FM the Model in Miniature (MiM) was developed to support a menu-less interaction (D2). It is an abstract representation of the displayed FM. It mimics the octree division of the FM and is able to display additional information about the regions. To be quickly at hand, it is placed above the user's controller as a scaled-down version of the FM (see Figure 1 (A) and Figure 2). The underlying idea of the MiM is based on the well-known World in Miniature (WIM) metaphor [27, Chapter 28] [4, 7, 35, 42]. In ImNDT we do not use a scaled down copy of the whole world, instead we create only one component that serves as an abstract miniature model. The MiM is therefore the downscaled octree representation of the complete data, which is leveraged as a visualization and interaction technique. This way the user gets an immediate overview of the octree subdivision for navigation and further exploration. The MiM acts as a **hand-held visualization (D6)**, which follows the movements of the controller and is directly linked to the FM to provide an **overview**. This is particularly useful, when users zoom in and out of the FM and are immersed in it during exploration to determine their own position and orientation relative to the fiber data. The orientation of the MiM is directly linked to the FM and therefore reflects the user's current point of view on the FM respectively.

Additionally, the MiM provides the possibility to display secondary information of the fiber data based on the octree regions. In case of fiber data, this could be information on fiber counts, orientation, length, etc. To facilitate the exploration of the multi-dimensional properties of the fiber data, the regions of the MiM, i.e., cubes, are color coded. With the spatial position of the regions in the FM represented by the color-coded cubes in the MiM, the abstract representation becomes a **3D heatmap (D4)**. The MiM supports the user in guiding the exploration by an overview of interesting regions, that can be found in the FM (e.g., regions of strongly varying orientations). A divergent color scheme, that is robust and easy to distinguish, was used in the encoding. This colorblind-safe design was chosen using the ColorBrewer tool by Harrower and Brewer [19]. The resulting color transfer function maps the weighted average, of each individual region, to the respective cube in the MiM. The weighted average, is calculated across all fibers and their characteristics for each region, weighted with the fiber's coverage percentage.

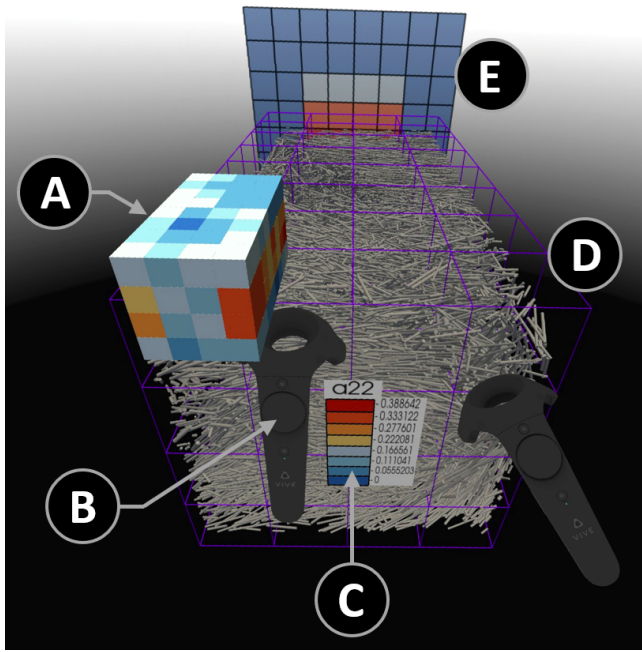


Figure 2: The MiM (A) is displayed as a colored 3D heatmap above the user's controller (B), with a color legend (C). In the center of the immersive workspace, the FM (D) is displayed, divided into regions by the octree structure. In the direction of the user's gaze, a MIP (E) is displayed.

The MiM is also used as a **spatial filtering** tool. Interactions such as selecting single or multiple octree regions in the MiM provides the ability for a more detailed analysis. The selected regions are marked in both the FM and abstract model, and fibers going through these selected regions are highlighted in red (Figure 1 (B) and Figure 3). Fibers from unselected regions are rendered semi-transparently to convey the spatial context of the selection. A selection is also possible directly in the FM, since both the FM and

the MiM are linked. The current **octree level**, indicating to which degree the FM is subdivided, is also communicated between the two representations. Changing the octree level, i.e., the level of subdivision for the whole FM is adjusted by touch input on the controller. Depending on whether the user increases or decreases the octree level, the currently displayed regions are divided into eight children or merged together. This allows the user to investigate fibers within the whole FM or in a very small region. The spatial representation as well as the calculation of the MiM's included 3D heatmap react to the interaction and update to the new subdivision. By changing the octree level, patterns that were hidden in the previous levels of the FM or 3D heatmap can be revealed.

3.3.2 Maximum Intensity Projection. To get a quick view of the highest values in the 3D heatmap even with a large number of regions, a Maximum Intensity Projection (MIP) is displayed to the user (see Figure 2 (E)) (D3). Based on the user's current viewing direction, axis-aligned parallel rays are sent through the FM and its regions, each storing the weighted average of the currently examined fiber characteristic. Only the highest average value, i.e., the maximum value, of all regions along a ray, is selected. Only one MIP plane, the one in the user's viewing direction (D2), is displayed at a time. The rays sent along the respective direction, i.e., the X-axis, Y-axis, or Z-axis, display the highest calculated value, as a 2D projection behind the FM. Here, a 2D representation allows for faster and easier interpretation than 3D alternatives, although the projection reduces the amount of information (D4). The projection plane contains the same number of rows and columns as formed by the octree subdivision. With the MIP, values inside can be estimated without having to look inside the MiM and without requiring an additional interaction (D6).

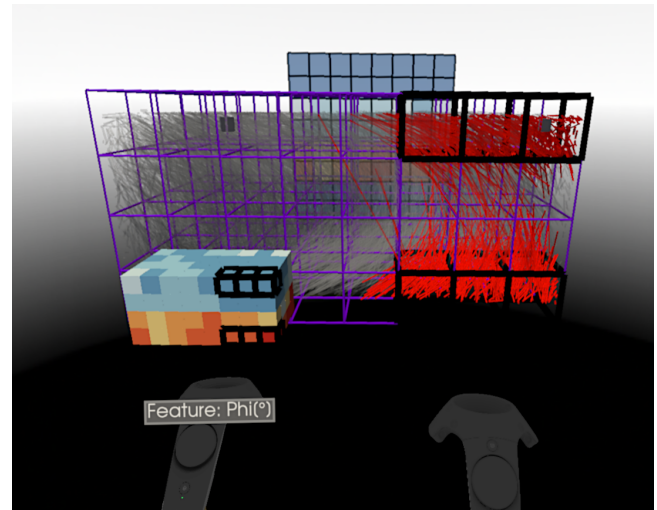


Figure 3: The user selects specific regions of interest in the MiM to investigate the individual fibers highlighted in red. Fibers in unselected regions are displayed semi-transparently to preserve spatial context.

3.3.3 Exploded View. Since outer regions in the MiM hide inner ones and fibers on the outside of the FM occlude the fibers in the inside, we use an exploded view to provide an unobstructed view of the inside. This technique is used for illustrative visualisations in many domains [5, 37, 38], where the structure or spatial context should be preserved, but the object of interest is occluded. For fiber-reinforced polymers, which can consist of more than a hundred thousand fibers, other approaches such as cutaways are typically not applicable because important contextual information and local relationships are lost. By using the exploded view, specific regions with their fibers can be detached by displacement from neighbouring regions and thus a view inside is facilitated to explore the interior without destroying the spatial context (see Figure 1 (A)). In our application there are several displacement methods for the exploded view (D3), which are applied to both the MiM and the FM due to the linking of these representations (see Figure 1 (B)). All three displacement types simultaneously move all regions with their fibers outward, away from the center of the FM. The *structure preserving displacement* increases the distance to the center and the regions, but the relative distances between the regions remain the same. All regions are shifted by their individual distance from the center, relative to the largest existing distance, thus preserving the overall structure of the FM. Another shift is the *radial displacement*. Here, all regions are displaced by the same factor, regardless of their distance from the center of the FM. All regions are therefore shifted outwards from the FM center, resulting in a radial arrangement of the regions. This changes the structure of the FM slightly, but offers the possibility of exposing a spherical space of which the inner structure can be better viewed. The *octant displacement* shifts the regions to the nearest octant out of eight possible octants. The center of the FM is the origin of the three-dimensional Euclidean coordinate system, which forms eight octants through the three axial planes X, Y, and Z. By moving the regions from the center of the FM outward the structure remains well preserved. All of these displacements can be used together to provide a type of *hybrid displacement*. The combination of displacements is used to decompose the FM and its abstract representation in a step-by-step process. It is possible to apply or undo all displacements and tear regions apart or merge them, giving domain experts the opportunity to analyze the structure and relationships of the regions.

Since in the FM fibers are displaced along with the regions they pass through, the result of the displacement of the fibers depends on the regions to which a fiber is assigned to. The assignment of a fiber is based on the coverage percentage of each region the fiber passes through. One possible assignment is to displace the fiber with each region in which it has a coverage. For instance, if a fiber is equally located in two different regions, the displacement is performed half in each direction. The other method provides a better separation of the regions, since it displaces the fibers only with the region in which they have the highest fiber coverage. Both methods create a form of clustering through the displacement, which divides the fibers into regions based on their coverages, making certain structures or patterns visible.

3.3.4 Similarity Network. Another way to discover patterns or structures in the data is by examining regions consisting of many fibers, or regions through which the same fibers are passing, i.e.,

regions that have fibers in common. Experts can change the FM to an abstracted representation (D3), in which the fibers are hidden (D7). Subregions are represented by cubes, where the size and color encode the number of fibers within the region and give a quick overview of the quantitative distribution of the fibers. Links display by thickness and color how many fibers the regions have in common, i.e., the similarity from one region to every other. By following the links between regions of high similarity, experts can more easily detect specific fiber orientations and by looking at the size of the cubes, identify regions where many fibers are located (see Figure 1 (C) and Figure 4). We use both size and color for the encoding to compensate for perspective distortions. The similarity between regions is calculated by a Jaccard index and can be thresholded by the user to highlight more similar or more dissimilar regions.

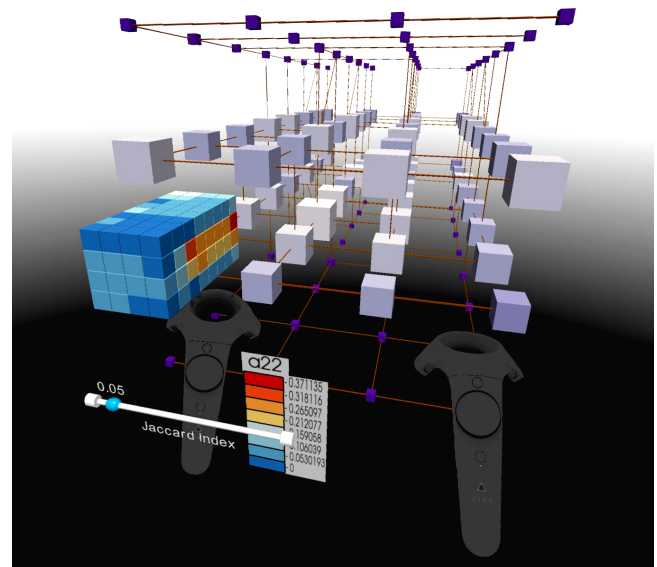


Figure 4: The FM represented as a similarity network: Regions are represented as cubes, which encode the number of fibers by size and color. The thickness and color of the lines indicate the degree of similarity between regions.

3.3.5 Histo-Book. Once interesting regions have been discovered through the similarity network, the expert can analyze them in more detail. The user can select up to two regions to examine and compare the distribution of their fiber characteristics. As a result, a histogram is calculated based on each fiber characteristic of the two regions and rendered in charts that are organized using a book metaphor. To provide domain experts with a familiar visual representation of histograms that is applicable in virtual environments, we designed the histo-book (see Figure 1 (D) and Figure 5). In the more distant half of a semi-transparent circular area, the charts are arranged and displayed like the sheets of a book. This results in an open book metaphor, in which each page represents the distribution of a specific fiber characteristic. The expert can switch between the charts, i.e., pages, by a page-turning gesture.

The design was chosen to allow natural exploration that does not interfere with the immersive experience caused by 2D billboards. Furthermore, the natural page-turning gesture provides an intuitive interaction that allows for a low learning curve. To avoid distractions by too many charts, only one chart of interest is in focus and highlighted (**D7**). The remaining pages of the histo-book are rendered semi-transparently to preserve overview and context and to reduce occlusions of the environment. Since the maxima and minima can be quickly distinguished by displaying the characteristic distributions of both regions using bars, this visualization method is well suited for quickly verifying hypotheses.

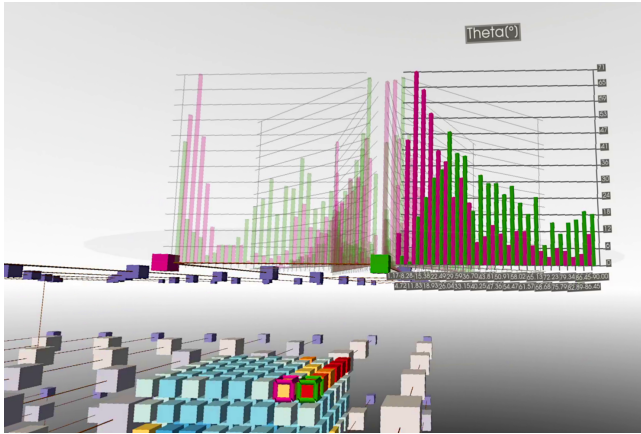


Figure 5: By selecting two regions in the MiM, the histo-book in the shape of an open book is displayed. The individual pages represent charts showing the distribution of a specific fiber characteristic.

4 USER STUDY

The goal of ImNDT is to provide users with immersive exploration tools that enable them to gain expected and, more importantly, unexpected insights for their work in the field of materials analysis. Our evaluation therefore aimed at getting realistic insights into the usability of the framework and how users can utilize the proposed visualization and interaction techniques. In order to test the usability in a real work scenario, our preference was primarily to invite domain experts for the study. The study was performed following all ethical and sanitary guidelines required at the time of execution. The vision of all participants was normal or corrected to normal to ensure that the results were not biased. The study consisted of an introduction to ImNDT, the exploration in the application, and a semi-structured interview. Our study took place with a desktop PC with an Intel i7-4770 and an NVIDIA GTX 1080, and an HTC Vive Pro Eye.

4.1 Participants

We recruited eleven participants (six female and five male users) aged between 25–56. All participants work in the field of materials science and use applications for the evaluation of XCT scans. Among the participants, six are domain experts in the field of FRP

analysis, and five novices. Nine of the participants have not used a VR application prior to this study.

4.2 Tasks & Datasets

A polypropylene (PP) matrix material reinforced with glass fibers was chosen as the dataset for the studies. The first dataset contained 19126 glass fibers and the second one 49618 fibers. Both datasets contain fibers attributed with 25 different characteristics. Since all participants had experience with the analysis of fiber datasets, an exploration task was specified in order to avoid restricting the workflow of the experts.

4.3 Procedure

For each participant the same process steps were followed in the study. In the first step, we started with an introduction to the application. We explained to the participants in approximately 15 minutes how to navigate with the controllers, the tools, and the possible actions in ImNDT. For the demonstration, the first dataset was always preloaded before the introduction began. Afterwards the participants were shown how to set up the HMD correctly and then the second dataset was loaded.

The participants afterwards had an average of 25 minutes to explore the virtual environment. During this time, they could use the application both sitting and standing, and in case of questions about the controls, the users could ask them. To get qualitative insights into the analysis process, we asked participants to use the "Thinking Aloud" approach during testing. They were asked to articulate, which actions they are currently planning and which conclusions they draw from what they have tried. Afterwards a semi-structured interview was prepared. The participants were asked open-ended questions about the underlying functions and metaphors within the system. The semi-structured interview lasted 25 minutes per participant and provided valuable feedback from the domain experts. After the semi-structured interview the participants were given a Likert Scale questionnaire (see Table 2).

5 RESULTS & DISCUSSION

Overall, participants liked ImNDT's new form of material exploration and found that it supported them very well in analyzing the spatial XCT datasets. Through the interview and from the questionnaire results, important metaphors were identified and the usefulness of our tools compared to the experts traditional tools were discovered.

5.1 Evaluation Results

The results of the questionnaire (see Table 2), based on a five point Likert Scale, reflect the feedback obtained. Each participant answered the twelve questions and the results are presented in Figure 6. The results of the questionnaire provided us with additional insights into the importance of certain immersive metaphors and tools. To evaluate the usefulness of our application, we considered answers with a score between 4 and 5 as a positive result, score 3 is a neutral result and the other scores indicate room for further improvement. As can be seen from the scores, the worst ranking (1) was not assigned. In general, the evaluation shows a very positive rating of the implemented visualization and interaction techniques.

Table 2: Questions for the evaluation of the implemented visualizations.

| Model in Miniature (MiM) | |
|--------------------------|---|
| Q1 | The MiM can support in navigating and orienting in the environment. |
| Q2 | The MiM can be used to discover similar/dissimilar feature distributions in the regions. |
| Q3 | Setting the octree level supported switching between overview and a more in-depth view. |
| Exploded View (EV) | |
| Q4 | The EV can improve the usability of the MiM. |
| Q5 | The EV can increase the overview on the FM. |
| Q6 | The different displacement modes of the EV can support exploration. |
| Similarity Network | |
| Q7 | The presentation of regions as cubes can support the overview of the fiber content. |
| Q8 | The visualization of the neighbourhood relations through links can supported the exploration. |
| Histo-Book | |
| Q9 | The comparison of two regions through the histo-book can support exploration. |
| Q10 | The focus and context visualization as book metaphor can improve the usability of the histograms. |
| Overview | |
| Q11 | The spatial representation can facilitate the exploration of fibers. |
| Q12 | The Maximum Intensity Projection can be a visual support for the exploration. |

5.2 Insights

To better reflect, which tools were most useful to the experts, we further discussed the thematic groups formed by the questionnaire in the interview.

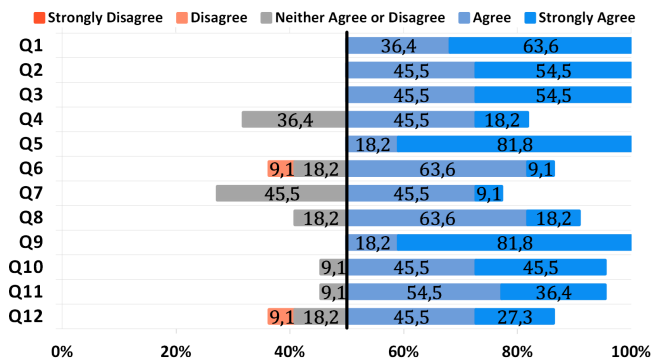


Figure 6: Evaluation results of the questionnaire, which was based on a Likert scale with scores ranging from 1 (strongly disagree) to 5 (strongly agree).

5.2.1 MiM. As can be seen by the solely positive reviews for each question **Q1**, **Q2**, **Q3** all participants considered the idea of an abstract, scaled-down FM very beneficial, as they found it intuitive and easy to use (**D2**). Furthermore, the participants stated that it helped them to keep their orientation in the virtual environment as well as in the 3D data, in particular as it moves with the user on the controller and thus cannot get lost in the environment (**Q1**). They liked the MiM's idea to display a 3D heatmap of specific fiber characteristics, because it allowed them to quickly identify regions of interest without changing the FM (**D6**, **D4**) (**Q2**). We also gained unexpected insights. For example, one participant reported that MiM "feels heavy" because it looks like a massive body, and therefore the controller feels tiring to use for extended periods of time. Participants noted positively that it was a good decision not to make the MiM rotatable by controller gestures, since they used the MiM as a reference to the FM and otherwise would have lost orientation. The selection of regions was very well perceived by the experts. Only one of the tested persons had problems with the selection of regions in the MiM. We suspect this is due to the selection area on the controller and the nature of the selection in the abstract model. The virtual point on the controller used for the selection is further back on the device, which means that the controller must be moved deep enough into the FM to allow selection. Users need to keep the left controller, over which the MiM hovers, stable enough to accurately select a region within the MiM with the right controller. One participant noted that it would be beneficial to freeze the MiM in the immersive space during the selection process and enlarge the MiM, to enable an easier selection of smaller regions (**D7**). We also noticed that despite the possibility to select regions in the FM, users preferred to interact with the MiM. A disadvantage of the multiselection, which was noticed by some participants, is that all fibers, regardless of the region, are highlighted with the same color. One possibility here would be to apply different colors or even to allow coloring based on a specific fiber characteristic (**D3**). By highlighting the most prominent fiber characteristic, for example, individual values of the fibers can be identified in addition to the average value of the region.

5.2.2 Exploded View. The participants found the exploded view very important for understanding the structure of the material. They also liked the fact that we offer several displacement methods, as this has a strong impact on the perceived structure (**D3**). One participant said "This [the exploded view] gives me a quick way to analyze the inside of the fiber model". The fact that the displacement of the FM is reflected in the MiM was also perceived positively in question **Q4**, although a too strong displacement can make the selection in the MiM a little more difficult. The participants also noted that in combination with the selection highlighting, the clustering effect is strongly visible. One user said "This [displacement of selected fibers] allows me to observe the fibers very well during shifting". Three participants reported that they only used the structure-preserving displacement and the octant shift, as these modes best maintained the overall structure of the FM. Therefore, the radial displacement helps them less, which led to the negative rating in **Q6**. All participants agreed that the exploded view technique is very engaging and effective in VR and a natural way to

interact with the FM (D6) as can be seen by the very positive rating in Q5.

5.2.3 Similarity Network. During the interview, we found that the usefulness strongly depended on the particular knowledge of the user. Experienced users were able to derive the information about the number of fibers through selections and the 3D heatmap of the MiM and usually did not need the network as can be seen by the rating of question Q7 (D7). Novice FRP users found visualizing the number of fibers in a region by nodes of varying sizes as useful. The ability to show relationships between regions was perceived as supportive and one participant stated *"The Jaccard index is very useful and might be helpful to see in the fiber model representation"* (D3). Therefore, question Q8, was positively received by 9 out of 11 participants.

5.2.4 Histo-Book. We found that experts in particular found the histo-book very helpful and rated it most positively in Q9, Q10. In their daily work, they are trained to make hypotheses using exact values. Therefore, it was very exciting for the experts to examine the hypotheses from the histograms directly on the FM (D5, D2), which resulted in all eleven ratings being positive, with nine of them giving the highest score in question Q9. The participants explained that the technique of highlighting the histogram they were looking at was not necessary, but did not distract from the analysis. They liked the transparency of the charts that are not in focus, i.e., remaining book pages, to keep the FM in view (D7) as seen by the rating of question Q10. Several participants also mentioned that a manual placement of the histo-book would be beneficial. One participant even said *"I find the MiM on the controller very helpful, so I could well imagine placing the histogram there as well"* (D6). In general, all participants found the book metaphor very intuitive and the applied page-turning interaction very natural (D2).

5.2.5 General Impression. We asked participants about the three-dimensional exploration of material data in ImNDT and how the immersive techniques influenced their analysis. They had the opportunity to give us additional feedback or suggestions. In general, the experts found the exploration of fiber datasets in immersive environments using a VR HMD to be helpful and positive. Question Q11 also suggests that experts would want to extend their current workflows to immersive environments. Eight participants mentioned the MIP positively and found the display of the representation behind the FM in the current viewing direction to be beneficial for gaining quick insights into the characteristic values. None of the participants found this interactive visualization distracting. Three experts argued that they did not need this representation because the internal values of the MiM could also be viewed via the displacement of the regions (D7) (Q12). Some participants noted 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 fiber model"* (D3). One expert suggested a short tutorial within the VR environment at the start to familiarize oneself more quickly with the controls in the immersive environment. We also asked the experts, how they experienced the immersive exploration and whether they missed any familiar elements from their traditional workflow. The participants all agreed that we prepared a very engaging exploration and

that they were able to work with less 2D charts (D4). However, they would like to add a coordinates system to better estimate sizes. They found the approach of subdividing the FM into eight children (through the octree structure) very helpful and would like to see this technique used in their conventional workstation-based applications. According to experts, ImNDT is specifically suited for curved fibers that cannot be efficiently tracked and analyzed using 2D slice views. The exploration in VR is particularly interesting for students, beginners and customers who need an intuitive and easy to perceive visualization.

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

6 CONCLUSION & FUTURE WORK

We have presented ImNDT, a new application for the analysis and exploration of multidimensional volumetric datasets. Our methods are being implemented in the open_iA framework [18], and are available as open source on GitHub [11]. The objective was to support experts in the field of materials science in their analysis workflows, which requires intuitive representations to support difficult cognitive tasks. We demonstrated the applicability of ImNDT to the analysis of FRP datasets from NDT tests through a qualitative evaluation with domain experts. We also reflected on the gathered feedback to further improve the workflow in material analysis. Our tool offers novices a valuable overview and detailed insights into the structure of the dataset, but for experts more numerical values need to be displayed. The analysis of the material's voxel data is also a valuable extension, which will become more feasible as the computing power of immersive devices and computers increases. Because our participants primarily preferred using ImNDT in a standing position, a future study based on this observation would also be of interest. The techniques described here can be applied to other domains as well. Our results open up promising new research opportunities for pores in composites or sponges. The overall positive feedback is encouraging for the field of immersive analytics of materials.

ACKNOWLEDGMENTS

We thank Christoph Anthes and the reviewers for their valuable feedback on our analysis methods and case studies. The research has received funding by research subsidies granted by the government of Upper Austria within the program line "Dissertationsprogramm der FH OÖ", grant no. 881298 "AugmeNDT" and the FTI "X-Pro" project, as well as partly from the Austrian Research Promotion Agency (FFG) within the program line "TAKE OFF", FFG grant no. 874540 "BeyondInspection". Part of the research was enabled by VRVis funded in COMET (879730) a program managed by FFG.

REFERENCES

- [1] Alexander Amirkhanov, Artem Amirkhanov, Dietmar Salaberger, Johann Kastner, M. Eduard Gröller, and Christoph Heinzl. 2016. Visual Analysis of Defects in Glass Fiber Reinforced Polymers for 4DCT Interrupted In situ Tests. *Computer Graphics Forum* 35, 3 (jun 2016), 201–210. <https://doi.org/10.1111/cgf.12896>
- [2] Andrea Batch, Andrew Cunningham, Maxime Cordeil, Niklas Elmqvist, Tim Dwyer, Bruce H. Thomas, and Kim Marriott. 2019. There Is No Spoon: Evaluating

- Performance, Space Use, and Presence with Expert Domain Users in Immersive Analytics. *IEEE Transactions on Visualization and Computer Graphics* (2019), 1–1. <https://doi.org/10.1109/tvcg.2019.2934803>
- [3] Arindam Bhattacharya, Johannes Weissenböck, Rephael Wenger, Artem Amirkhanov, Johann Kastner, and Christoph Heinzl. 2017. Interactive Exploration and Visualization Using MetaTracts extracted from Carbon Fiber Reinforced Composites. *IEEE Transactions on Visualization and Computer Graphics* 23, 8 (aug 2017), 1988–2002. <https://doi.org/10.1109/tvcg.2016.2582158>
 - [4] Andrew Bluff and Andrew Johnston. 2019. Don't Panic: Recursive Interactions in a Miniature Metaworld. In *The 17th International Conference on Virtual-Reality Continuum and its Applications in Industry*. ACM. <https://doi.org/10.1145/3359997.3365682>
 - [5] Stefan Bruckner and M. Eduard Gröller. 2006. Exploded Views for Volume Data. *IEEE Transactions on Visualization and Computer Graphics* 12, 5 (Sep. 2006), 1077–1084. <https://doi.org/10.1109/TVCG.2006.140>
 - [6] Tom Chandler, Maxime Cordeil, Tobias Czuderna, Tim Dwyer, Jaroslaw Glowacki, Catagay Goncu, Matthias Klapperstück, Karsten Klein, Kim Marriott, Falk Schreiber, and Elliot Wilson. 2015. Immersive Analytics. (sep 2015). <https://doi.org/10.1109/bdva.2015.7314296>
 - [7] Dane Coffey, Nicholas Malbraaten, Trung Bao Le, Iman Borazjani, Fotis Sotiropoulos, Arthur G. Erdman, and Daniel F. Keefe. 2012. Interactive Slice WIM: Navigating and Interrogating Volume Data Sets Using a Multisurface, Multitouch VR Interface. *IEEE Transactions on Visualization and Computer Graphics* 18, 10 (oct 2012), 1614–1626. <https://doi.org/10.1109/tvcg.2011.283>
 - [8] Maxime Cordeil, Andrew Cunningham, Benjamin Bach, Christophe Hurter, Bruce H. Thomas, Kim Marriott, and Tim Dwyer. 2019. IATK: An Immersive Analytics Toolkit. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 200–209. <https://doi.org/10.1109/VR.2019.8797978>
 - [9] Maxime Cordeil, Andrew Cunningham, Tim Dwyer, Bruce H. Thomas, and Kim Marriott. 2017. ImAxes. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology - UIST '17*. ACM Press. <https://doi.org/10.1145/3126594.3126613>
 - [10] Carolina Cruz-Neira, Daniel J. Sandin, Thomas A. DeFanti, Robert V. Kenyon, and John C. Hart. 1992. The CAVE: audio visual experience automatic virtual environment. *Commun. ACM* 35, 6 (jun 1992), 64–72. <https://doi.org/10.1145/129888.129892>
 - [11] CTVis group (3dct). 2021. open_iA: A tool for the visual analysis and processing of volumetric datasets, with a focus on industrial computed tomography. https://3dct.github.io/open_iA/. [Online; accessed 07-October-2021].
 - [12] Margaret Drouhard, Chad A. Steed, Steven Hahn, Thomas Proffen, Jamison Daniel, and Michael Matheson. 2015. Immersive visualization for materials science data analysis using the Oculus Rift. In *2015 IEEE International Conference on Big Data (Big Data)*. IEEE, 2453–2461. <https://doi.org/10.1109/bigdata.2015.7364040>
 - [13] Barrett Ens, Benjamin Bach, Maxime Cordeil, Ulrich Engelke, Marcos Serrano, Wesley Willett, Arnaud Prouzeau, Christoph Anthes, Wolfgang Büschel, Cody Dunne, Tim Dwyer, Jens Grubert, Jason H. Haga, Nurit Kirshenbaum, Dylan Kobayashi, Tica Lin, Monsurat Olaosebikan, Fabian Pointecker, David Saffo, Nazmus Saquib, Dieter Schmalstieg, Danielle Albers Szafir, Matt Whitlock, and Yalong Yang. 2021. Grand Challenges in Immersive Analytics, In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. *CHI Conference on Human Factors in Computing Systems (CHI'21)*, 8–13. <https://doi.org/10.1145/3411764.3446866>
 - [14] Jorge A. Wagner Filho, Carla M. D. S. Freitas, and Luciana Nedel. 2019. Comfortable Immersive Analytics With the VirtualDesk Metaphor. *IEEE Computer Graphics and Applications* 39, 3 (may 2019), 41–53. <https://doi.org/10.1109/mcg.2019.2898856>
 - [15] Jorge A. Wagner Filho, Marina F. Rey, Carla M. D. S. Freitas, and Luciana Nedel. 2018. Immersive Visualization of Abstract Information: An Evaluation on Dimensionally-Reduced Data Scatterplots. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 483–490. <https://doi.org/10.1109/vr.2018.8447558>
 - [16] Adrien Fonnet and Yannick Prie. 2019. Survey of Immersive Analytics. *IEEE Transactions on Visualization and Computer Graphics* (2019). <https://doi.org/10.1109/tvcg.2019.2929033>
 - [17] Blender Foundation. 2021. Blender Website. <https://www.blender.org/>. [Online; accessed 07-October-2021].
 - [18] Bernhard Fröhler, Johannes Weissenböck, Marcel Schiwarth, Johann Kastner, and Christoph Heinzl. 2019. open_iA: A tool for processing and visual analysis of industrial computed tomography datasets. *Journal of Open Source Software* 4, 35 (mar 2019), 1185. <https://doi.org/10.21105/joss.01185>
 - [19] Mark Harrower and Cynthia A. Brewer. 2003. ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps. *The Cartographic Journal* 40, 1 (jun 2003), 27–37. <https://doi.org/10.1179/000870403235002042>
 - [20] Devamardeep Hayatpur, Haijun Xia, and Daniel Wigdor. 2020. DataHop: Spatial Data Exploration in Virtual Reality. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. ACM. <https://doi.org/10.1145/3379337.3415878>
 - [21] Christoph Heinzl, Robert Michael Kirby, Stepan V. Lomov, Guillermo Requena, and Rüdiger Westermann. 2019. Visual Computing in Materials Sciences (Dagstuhl Seminar 19151). *Dagstuhl Reports* 9, 4 (2019), 1–42. <https://doi.org/10.4230/DagRep.9.4.1>
 - [22] Christoph Heinzl and Stefan Stappen. 2017. STAR: Visual Computing in Materials Science. *Comput. Graph. Forum* 36, 3 (June 2017), 647–666. <https://doi.org/10.1111/cgf.13214>
 - [23] Christophe Hurter, Nathalie Henry Riche, Steven M. Drucker, Maxime Cordeil, Richard Alligier, and Romain Vuillemot. 2019. FiberClay: Sculpting Three Dimensional Trajectories to Reveal Structural Insights. *IEEE Transactions on Visualization and Computer Graphics* 25, 1 (jan 2019), 704–714. <https://doi.org/10.1109/tvcg.2018.2865191>
 - [24] Nathan Ida. 2019. *Handbook of Advanced Nondestructive Evaluation*. Springer International Publishing, Cham, Switzerland. <https://doi.org/10.1007/978-3-319-26553-7>
 - [25] Alexander Ivanov, Kurtis Danyluk, Christian Jacob, and Wesley Willett. 2019. A Walk Among the Data. *IEEE Computer Graphics and Applications* 39, 3 (may 2019), 19–28. <https://doi.org/10.1109/mcg.2019.2898941>
 - [26] Bret Jackson, Tung Yuen Lau, David Schroeder, Kimani C. Toussaint, and Daniel F. Keefe. 2013. A Lightweight Tangible 3D Interface for Interactive Visualization of Thin Fiber Structures. *IEEE Transactions on Visualization and Computer Graphics* 19, 12 (dec 2013), 2802–2809. <https://doi.org/10.1109/tvcg.2013.121>
 - [27] Jason Jerald. 2015. *The VR Book*. Association for Computing Machinery and Morgan & Claypool. <https://doi.org/10.1145/2792790>
 - [28] Kitware. 2021. Paraview Website. <https://www.paraview.org/desktop/>. [Online; accessed 07-October-2021].
 - [29] Matthias Kraus, Katrin Angerbauer, Juri Buchmüller, Daniel Schweitzer, Daniel A. Keim, Michael Sedlmair, and Johannes Fuchs. 2020. Assessing 2D and 3D Heatmaps for Comparative Analysis. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM. <https://doi.org/10.1145/3313831.3376675>
 - [30] Matthias Kraus, Niklas Weiler, Daniela Oelke, Johannes Kehrler, Daniel A. Keim, and Johannes Fuchs. 2020. The Impact of Immersion on Cluster Identification Tasks. *IEEE Transactions on Visualization and Computer Graphics* 26, 1 (jan 2020), 525–535. <https://doi.org/10.1109/tvcg.2019.2934395>
 - [31] Bireswar Laha, Doug A. Bowman, and John J. Socha. 2016. Bare-Hand Volume Cracker for Raw Volume Data Analysis. *Frontiers in Robotics and AI* 3 (sep 2016). <https://doi.org/10.3389/frobt.2016.00056>
 - [32] Bireswar Laha, Kriti Sensharma, James D. Schiffbauer, and Doug A. Bowman. 2012. Effects of Immersion on Visual Analysis of Volume Data. *IEEE Transactions on Visualization and Computer Graphics* 18, 4 (apr 2012), 597–606. <https://doi.org/10.1109/tvcg.2012.42>
 - [33] Jiazhou Liu, Arnaud Prouzeau, Barrett Ens, and Tim Dwyer. 2020. Design and Evaluation of Interactive Small Multiples Data Visualisation in Immersive Spaces. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 588–597. <https://doi.org/10.1109/vr46266.2020.00081>
 - [34] Kim Marriott. 2018. *Immersive analytics*. Springer, Cham, Switzerland. <https://doi.org/10.1007/978-3-030-01388-2>
 - [35] Jung Who Nam, Krista McCullough, Joshua Tveite, Maria Molina Espinosa, Charles H. Perry, Barry T. Wilson, and Daniel F. Keefe. 2019. Worlds-in-Wedges: Combining Worlds-in-Miniature and Portals to Support Comparative Immersive Visualization of Forestry Data. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 747–755. <https://doi.org/10.1109/vr.2019.8797871>
 - [36] Dipen Rajak, Durgesh Pagar, Pradeep Menezes, and Emanoil Linul. 2019. Fiber-Reinforced Polymer Composites: Manufacturing, Properties, and Applications. *Polymers* 11, 10 (oct 2019), 1667. <https://doi.org/10.3390/polym11101667>
 - [37] Marc Ruiz, Ivan Viola, Imma Boada, Stefan Bruckner, Miquel Feixas, and Mateu Sbert. 2008. Similarity-Based Exploded Views. *Springer-Verlag Berlin Heidelberg* (2008), 154–165. https://doi.org/10.1007/978-3-540-85412-8_14
 - [38] Maximilian Sbardellati, Haichao Miao, Hsiang-Yun Wu, M. Eduard Gröller, Ivan Barisic, and Ivan Viola. 2019. Interactive Exploded Views for Molecular Structures. In *Proceedings of the 9th Eurographics Workshop on Visual Computing for Biology and Medicine*. <https://www.cg.tuwien.ac.at/research/publications/2019/Sbardellati-2019-vcbm/>
 - [39] Jürgen Schulze-Döbold, Uwe Wössner, Steffen P. Walz, and Ulrich Lang. 2001. Volume Rendering in a Virtual Environment, In *Eurographics Workshop on Virtual Environments*, B. Froehlich, J. Deisinger, and H.-J. Bullinger (Eds.). *Eurographics Workshop on Virtual Environments*. <https://doi.org/10.2312/EGVE/EGVE01/187-198>
 - [40] Roman Shkarin, Andrei Shkarin, Svetlana Shkarina, Angelica Cecilia, Roman A. Surmenev, Maria A. Surmeneva, Venera Weinhardt, Tilo Baumbach, and Ralf Mikut. 2019. Quanfima: An open source Python package for automated fiber analysis of biomaterials. *PLOS ONE* 14, 4 (apr 2019). <https://doi.org/10.1371/journal.pone.0215137>
 - [41] Johannes Sorger, Manuela Waldner, Wolfgang Knecht, and Alessio Arleo. 2019. Immersive Analytics of Large Dynamic Networks via Overview and Detail Navigation. In *2019 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, 144–1447. <https://doi.org/10.1109/aivr46125.2019.00030>

- [42] Richard Stoakley, Matthew J. Conway, and Randy Pausch. 1995. Virtual reality on a WIM. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '95*. ACM Press. <https://doi.org/10.1145/223904.223938>
- [43] Thermo Fisher Scientific. 2021. 3D Visualization & Analysis Software Website. <https://www.thermofisher.com/at/en/home/industrial/electron-microscopy/electron-microscopy-instruments-workflow-solutions/3d-visualization-analysis-software/avizo-materials-science.html>. [Online; accessed 07-October-2021].
- [44] Unity Technologies Unity. 2021. Unity Website. <https://unity.com/>. [Online; accessed 07-October-2021].
- [45] Volumegraphics. 2021. VGSTUDIO MAX Website. <https://www.volumegraphics.com/de/produkte.html>. [Online; accessed 07-October-2021].
- [46] Song Wang, Dong Zhu, Hao Yu, and Yadong Wu. 2020. Immersive WYSIWYG (What You See is What You Get) Volume Visualization. (jun 2020). <https://doi.org/10.1109/pacificvis48177.2020.1001>
- [47] Johannes Weissenböck, Artem Amirkhanov, Weimin Li, Andreas Reh, Alexander Amirkhanov, Eduard Gröller, Johann Kastner, and Christoph Heinzl. 2014. FiberScout: An Interactive Tool for Exploring and Analyzing Fiber Reinforced Polymers. In *2014 IEEE Pacific Visualization Symposium*. IEEE. <https://doi.org/10.1109/pacificvis.2014.52>
- [48] Yalong Yang, Maxime Cordeil, Johanna Beyer, Tim Dwyer, Kim Marriott, and Hanspeter Pfister. 2021. Embodied Navigation in Immersive Abstract Data Visualization: Is Overview+Detail or Zooming Better for 3D Scatterplots? *IEEE Transactions on Visualization and Computer Graphics* 27, 2 (2021), 1214–1224. <https://doi.org/10.1109/TVCG.2020.3030427>
- [49] Yalong Yang, Tim Dwyer, Kimbal Marriott, Bernhard Jenny, and Sarah Goodwin. 2020. Tilt Map: Interactive Transitions Between Choropleth Map, Prism Map and Bar Chart in Immersive Environments. *IEEE Transactions on Visualization and Computer Graphics* (2020), 1–1. <https://doi.org/10.1109/tvcg.2020.3004137>
- [50] Fangfang Zhou, Xiaoru Lin, Chang Liu, Ying Zhao, Panpan Xu, Liu Ren, Tingmin Xue, and Lei Ren. 2018. A survey of visualization for smart manufacturing. *Journal of Visualization* 22, 2 (nov 2018), 419–435. <https://doi.org/10.1007/s12650-018-0530-2>