

FiberScout: An Interactive Tool for Exploring and Analyzing Fiber Reinforced Polomers

Johannes Weissenböck*
University of Applied
Sciences Upper Austria -
Wels Campus

Alexander Amirkhanov[¶]
Ufa State Aviation Technical
University, Ufa, Russia

Artem Amirkhanov[†]
University of Applied
Sciences Upper Austria -
Wels Campus

Eduard Gröller^{||}
Vienna University of
Technology, Institute of
Computer Graphics and
Algorithms, Vienna, Austria

Weimin Li[‡]
University of Applied
Sciences Upper Austria -
Wels Campus

Johann Kastner^{**}
University of Applied
Sciences Upper Austria -
Wels Campus

Andreas Reh[§]
University of Applied
Sciences Upper Austria -
Wels Campus

Christoph Heinzl^{††}
University of Applied
Sciences Upper Austria -
Wels Campus

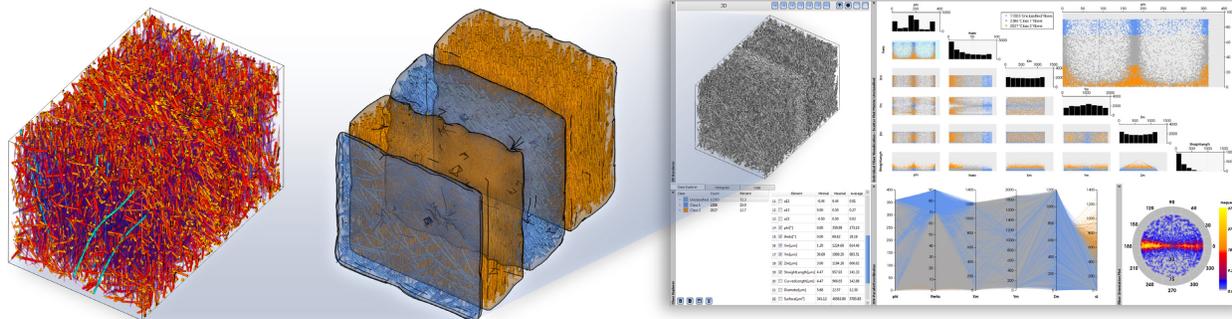


Figure 1: Glass fiber reinforced polymer (GFRP) visualized using the *FiberScout* system.

ABSTRACT

Advanced composites such as fiber reinforced polymers are promising candidate materials for future components as they allow integrating the continuously rising demands of industry regarding cost-effectiveness, function-orientation, integration and weight. The most important structures of fiber reinforced polymers are the individual fibers, as their characteristics (stiffness, strength, ductility, durability, etc.) to a large extent determine the properties of the final component. The main contribution of this paper is the introduction of a new system for interactive exploration and visual analysis of fiber properties in X-ray computed tomography data of fiber reinforced polymers. The presented tool uses parallel coordinates to define and configure initial fiber classes. Using a scatter plot matrix linked to the parallel coordinates the initial classification may be refined. This allows to analyze hidden relationships between individual fiber properties. 2D and 3D views depict the resulting fiber classifications. By using polar plots an intuitive rendering of the fiber orientation distribution is provided. In addition, two modules of higher abstraction are proposed: The Blob visualization creates

a hull around fibers with similar characteristics. The fiber metadata visualization allows to calculate overlays for 2D and 3D views containing regional information of particular material characteristics. The proposed system has been evaluated by two groups of domain experts. Applying the presented concepts the user feedback shows that the domain experts are now able to efficiently perform tasks as classification of fibers, visualization of fiber lengths and orientations, and visualization of fiber regions. The insights gained can be forwarded to the design office as well as to material development and simulation, in order to speed up the development of novel composite components.

Index Terms: I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques

1 INTRODUCTION

In modern industry a clear trend evolved of moving industrial research towards new cost-effective, function-oriented, highly integrated and light-weight components. This novel trend is mainly caused by growing demands in terms of efficiency, environment, safety as well as comfort. Especially the aviation industry and more recently also automotive, leisure and other industries have found a promising candidate class of materials meeting these high demands in advanced composite materials.

Advanced composite materials and more specifically fiber reinforced polymers (FRPs) make up a growing proportion in high tech industrial products. For example, in next-generation aircrafts, more than 50% of the complete aircraft will be made of fiber reinforced polymers [24]. Due to the increasing share of advanced composite materials also the demand for non-destructive testing (NDT) methods is rapidly growing [20]. As the characteristics of individual fibers in FRP components contribute to a great ex-

*e-mail: johannes.weissenboeck@fh-wels.at

[†]e-mail: artem.amirkhanov@fh-wels.at

[‡]e-mail: li.weimin@fh-wels.at

[§]e-mail: andreas.reh@fh-wels.at

[¶]e-mail: alexander.msg@gmail.com

^{||}e-mail: groeller@cg.tuwien.ac.at

^{**}e-mail: johann.kastner@fh-wels.at

^{††}e-mail: christoph.heinzl@fh-wels.at

tent to the final characteristics in terms of stiffness, strength, ductility and durability, the domain experts are highly interested in non-destructive, qualitative and quantitative analyses. For example, quantities such as fiber orientation distribution (FOD), fiber length distribution (FLD) or fiber content are highly important parameters for the prediction of tensile strength of short-fiber reinforced polymers [6, 28]. Therefore, getting insight into the characteristics of individual fibers without destroying the specimen is crucial for domain experts to improve and optimize the material as well as the design of new parts.

Industrial 3D X-Ray computed tomography (XCT) has rapidly evolved in the field of non-destructive testing within recent years and is now increasingly applied for quality control and metrology. State of the art industrial XCT devices are capable of generating high resolution volume data at voxel sizes of $1 \mu m$ or even below. The main benefit of high resolution XCT volume data for NDT practitioners is to get a comprehensive and highly detailed analysis of the test specimen. However, due to the high information content of the volume data, data exploration and visualization has become a big challenge.

When analyzing an FRP sample the domain experts are interested in how the fibers are distributed according to length and orientation. Depending on the given lengths and how the fibers are aligned experts can then estimate and verify the material properties. They are looking for fiber layers (different by their orientation), resulting from the manufacturing process. Furthermore, it is important for the experts which fiber characteristics a spatial sub-region has. These insights can be used for subsequent simulations. In addition another question for material experts is, how the individual fiber properties relate to each other and which regularities can be derived from them. Currently, the domain experts are using specific software products such as *VG Studio Max* and its *Materials Fiber Composite Analysis Module* [29] to examine FRP materials. With this module, local and global orientations as well as concentrations of fibers can be displayed in a 3D view and a 2D slice view. But it is not possible to search for specific fiber properties within a sample and there is no visual highlighting or classification for fibers. In addition, no dependencies between the individual fiber characteristics can be investigated and no visualizations on a higher abstraction level are provided.

Based on the domain-specific requirements the following tasks for fiber characterization and fiber visualization using XCT have been identified:

Task 1: Classification of fibers. The most important task is to identify and visualize classes of individual fibers in XCT scans of FRP samples. The domain experts need interactive visualization techniques to define and configure fiber classes in accordance to their specific properties and to individually render each class.

Task 2: Visualization of fiber lengths and orientations. Fiber lengths and fiber orientations contribute to a large extent to the characteristics of the final components such as strength or stiffness. Therefore the domain experts need visualization techniques to render the fiber length and orientation distribution in the dataset.

Task 3: Visualization of fiber regions. The domain experts require a quick and easy solution to identify and visualize regions with similar fiber characteristics. A hull has to be determined, which is enclosing regions of fibers with similar characteristics and clearly differentiate themselves from other regions. The domain experts need a method to analyze the manufacturing process in order to determine modifications in the layer structure of the material. Furthermore, methods are required to quickly explore the data and to identify relationships between individual fiber characteristics.

In order to address the tasks identified by the domain experts, we introduce the *FiberScout*, a system to visualize and explore XCT scans of fiber reinforced composites. The analysis work flow starts with an XCT scan of the specimen and thus the generation of data.

In a preprocessing step a label image is calculated from the original gray value image, which is used as basis for all developed techniques. The main contributions of this work are found in the designed techniques and their domain specific integration as well as in the solutions for tasks 1 - 3 identified by domain specialists (see Figure 2):

Parallel coordinates and scatter plot matrix to classify fibers. In order to analyze the internal micro-structure of the specimen, parallel coordinates and a scatter plot matrix classify the fibers according to fiber characteristics. The scatter plot matrix is used to refine the classification results from the parallel coordinates in a further step. Furthermore, the scatter plot matrix allows to reveal hidden relationships between fiber characteristics.

Polar plots to render fiber orientations. The fiber orientation distribution (FOD) is computed on a half sphere and visualized using the azimuthal projection of the northern hemisphere on a 2D plane. A spherical color map is integrated to color code the orientations of fibers in 3D as specified by the domain experts.

Blob visualization and fiber metadata visualization to render fiber classes. In order to address the problem of occlusion and clutter when rendering datasets with high fiber content, a smooth hull (blob) is extracted and rendered. It shows regions of fibers with similar characteristics or fiber bundles. Each identified region is visualized as a single blob. Furthermore regional meta information of the fiber data is computed for the fiber metadata visualization to quickly explore the dataset.

In the subsequent section we review the related work on fiber analysis and fiber visualization. In Section 3 the data generation, the datasets and the data preprocessing are described. In Section 4, the visualization techniques to address task 1-3 are introduced. Section 5 presents the evaluation of the visualization results. Finally, we conclude and point out potential future work in Section 6.

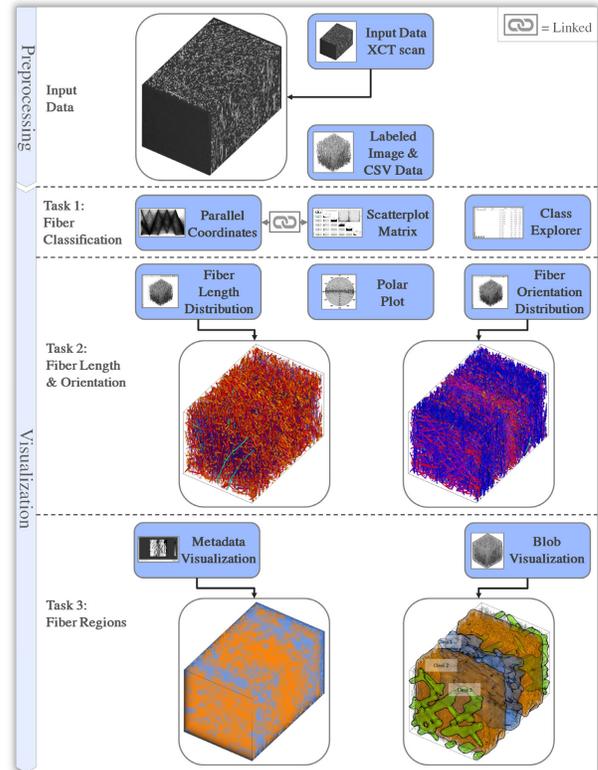


Figure 2: Overview of the *FiberScout* visualization techniques.

2 RELATED WORK

The related work for the proposed techniques is mainly found in the visualization and analysis of material systems, parameter space exploration as well as visual data exploration techniques.

2.1 Visualization and Analysis of Material Systems

Initial visualization techniques for non-destructive testing using industrial XCT data have been first introduced by Huang et al. [10]. A method for visualizing a pre-computed feature volume with a time series of domain parameters using 3D transfer functions was presented by Hadwiger et al. [8]. Based on this method, Fritz et al. [5] introduced an approach to explore steel fiber reinforced sprayed concrete and to quantify fiber properties such as fiber orientation. They use a direction sphere histogram to visualize the fiber orientation distribution. Furthermore direction transfer functions in the orientation domain are used to visualize fiber orientations with user specified colors. The field of application of Fritz' work is in comparison to our application area of FRPs a completely different one. We can calculate far more individual fiber characteristics of FRPs and we can represent each characteristic in charts. Furthermore, we can search for fibers with a highly specific set of fiber features and classify them. Besides these differences, we employ several abstract representations to visualize fiber characteristics and the defined fiber classes.

Regarding orientation visualization, Robb et al. [21] presented a method to calculate the local orientation of a fiber using a Gaussian orientation space. Altendorf and Jeulin [1] compute the local directions in continuous space by analyzing the mathematical morphology of images. A disadvantage of the local orientation analysis is that a single fiber may have various orientations, as the calculation is done on a pixel or voxel-basis. This is not suitable for visualizing fibers as a whole object in our visualization pipeline.

The algorithm described by Salaberger et al. [22] and Teßmann et al. [27] is used to extract individual fibers in our visualization pipeline. Tests included in their work demonstrated that the methods produces results with accuracies of more than 95% correctly detected fibers (mainly depending on the fiber content). Based on this implementation further algorithms are applied for the calculation of fiber properties (e.g., fiber orientation, fiber length, fiber diameter, fiber volume). Fiber orientations are then visualized in 3D space with a domain specific spherical color map based on the work of Yamrom et al. [31].

2.2 Parameter Space Exploration

Parallel coordinates [11] and scatter plots [30] are popular techniques for visualizing high-dimensional data sets. For example, Craig et al. [4] use coordinated parallel views to query micro array time-course data. The queries done in the coordinated parallel view are then linked to a scatter plot. They conclude that the coordinated parallel view is more appropriate for revealing details in the data and supporting the discovery of less dominant patterns. S-style axis layout parallel coordinates are used by Qu et al. [19] to highlight wind directions for analyzing the air pollution problem in Hong Kong. This approach is suitable for revealing correlations between 1D directions and other variables. However for analyzing 3D directions together with spatial information conventional parallel coordinates are more convenient. Kuang et al. [15] did a comparison of scatter plots and parallel coordinates. They found that parallel coordinates show advantages in low dimensionality and low density datasets, while scatter plots outperform parallel coordinates in higher dimensionality and higher density datasets. Parallel coordinates and a scatter plot matrix are integrated in our visualization pipeline. We combine the two techniques using *linking* and *brushing* [14], in order to explore the data in a more interactive way. The advantages of these two techniques are exploited and hidden correlations between individual characteristics are easier to detect.

2.3 Visual Exploration

Regarding clustering methods, Zhou et al. [33] introduced splatting of the individual lines in parallel coordinates to reveal strong correlations between the dimensions and to detect trends. In addition Zhou et al. [32] proposed a novel method using parallel coordinates for multi-dimensional transfer function design. Guo et al. [7] present an effective transfer function (TF) design for multivariate volumes, providing tightly coupled views of parallel coordinates plots. Li et al. [16] showed a novel approach for space deformation to simulate a magnification lens on versatile volume datasets and textured solid models. Tatu et al. [26] employ interestingness-guided subspace search algorithms to detect a candidate set of subspaces. The result of a *k-means* [13] algorithm turned out to generate robust consequences for initial automatic classifications. Therefore, in our proposed work we follow this approach for the determination of fiber classes with similar characteristics. Jackson et al. [12] present a tangible interface which allows a 3D interactive exploration of thin fiber structures to understand patterns in fiber orientation inside a volume.

3 DATA GENERATION AND PREPROCESSING

This section briefly explains how the industrial X-ray computed tomographic data is generated (see Section 3.1), which datasets are used (see Section 3.2), and how the preprocessing step performs calculations on fiber characteristics and individual fiber extractions (see Section 3.3).

3.1 Data Generation

Industrial X-ray computed tomography (XCT) provides a 3D volumetric representation of the scanned specimen. The specimen is placed on a rotary table between an X-ray source and a detector. The specimen is penetrated by X-rays. It attenuates the incident X-rays according to material properties and penetration thickness [9]. The detector converts the radiation intensity into digital projection images, which are finally reconstructed into a 3D volume data.

3.2 Dataset Descriptions

The two glass fiber reinforced polymer (GFRP) specimens to test the fiber visualization pipeline are $614 \times 961 \times 600$ and $608 \times 1411 \times 500$ voxels in size with a resolution of $2 \mu\text{m}$ and $3 \mu\text{m}$ respectively. We will subsequently call them *dataset1* (see Figure 3A) and *dataset2* (see Figure 3B). The carbon fiber reinforced polymer (CFRP) specimen we investigated in this work has a size of $600 \times 500 \times 600$ voxels and is scanned with a resolution of $1 \mu\text{m}$. We will subsequently call it *dataset3*. All specimens are scanned with a GE phoenix|X-Ray Nanotom 180.

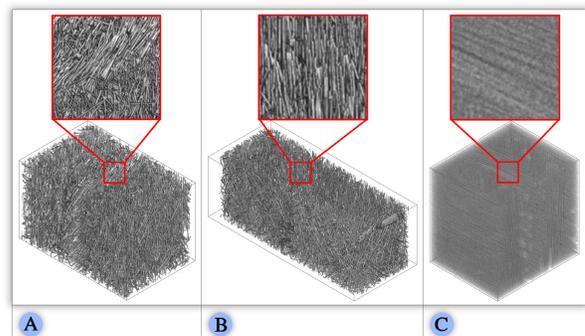


Figure 3: 3D rendering of the datasets used in this paper. (A) GFRP specimen (*dataset1*), 15916 fibers. (B) GFRP specimen (*dataset2*), 21751 fibers. (C) CFRP specimen (*dataset3*), 22656 fibers.

Characteristic	Description	Unit
a_{11}, a_{22}, a_{33}	The main diagonal elements of the fiber orientation tensor [25]	-
φ, θ	Spherical coordinates of a fiber orientation	$^\circ$
X_i, Y_i, Z_i	Cartesian coordinates of the i^{th} fiber center point, $0 \leq i \leq m-1$	μm
sL	Straight length of a fiber	μm
$diameter$	Diameter of a fiber	μm
$volume$	Volume of a fiber	μm^3

Table 1: Most significant fiber characteristics, identified by the domain experts.

3.3 Preprocessing

In the preprocessing step the fiber characterization pipeline (FCP) according to Salaberger et al. [22] is applied to the scanned XCT volume data of the fiber reinforced polymer (FRP) specimens. In the first step of this pipeline Gaussian blurring is applied to reduce noise in the original volume data. In the second step the gradient magnitude is computed, which is used as input for the computation of the Hessian matrix at each voxel. Using the Hessian matrix, the gray value differences of a voxel compared to its neighboring voxels are detected, which allows to deduce the main orientation of fibers. The Hessian matrix also determines the medial axis of the individual fibers as originally proposed by Teßmann et al. [27]. The intermediate results of the pipeline are the extracted individual fibers of the dataset given by their corresponding start and end points. The characteristics of the extracted fibers are computed at the same time as the individual fibers are extracted. Finally a labeling filter is applied to all the extracted fibers. In the labeled image every voxel of an individual fiber is mapped to a unique label identification. In total, 25 fiber characteristics for each fiber are available. The most significant fiber characteristics for further analysis are shown in Table 1.

4 VISUALIZATION

For understanding the micro structures of fiber reinforced polymers, visualization techniques such as direct volume rendering of the extracted fibers do not satisfy the requirements of the domain specialists. This is due to clutter and occlusion. To overcome this problem, the *FiberScout* system (see Figure 1 on the right) with its visual fiber exploration techniques (Section 4.1) has been developed allowing interactive data exploration, clustering and classification. Therefore, parallel coordinates (Section 4.1.1) are linked to a scatter plot matrix (Section 4.1.2), the fiber class explorer (Section 4.1.3) as well as to 2D and 3D views. Furthermore, visualization techniques have been developed to give insight into the clustered fiber data at a higher level of abstraction. These widgets and techniques include the fiber orientation distribution (Section 4.2), the fiber length distribution (Section 4.3), the blob visualization (Section 4.4), and the fiber metadata visualization (Section 4.5).

4.1 Visual Fiber Exploration

Right after loading the dataset into the visualization pipeline, an *overview* of the data is presented in parallel coordinates (PC), in a scatter plot matrix (SPM) as well as in a 3D view. Following the visual information-seeking mantra described by Shneiderman [23], the data is divided into subclasses (*zoom and filter*), which are displayed in turn in parallel coordinates and the scatter plot matrix.

The clutter and occlusion problem of the visualization may be considerably reduced using additional user-specified queries to the data (*details on demand*). Furthermore, the views of PC and SPM are linked together. Changes done in the parameter space will immediately be applied to the data (3D view and slice views) so that the user is able to get a real-time feedback when querying the data. This concept supports interactivity and makes the visual exploration process clearer and simpler.

4.1.1 Parallel Coordinates for Fibers

Parallel coordinates (PC) [11] is a powerful visualization technique using high-dimensional geometry for the analysis of multivariate data. Unlike in the Cartesian coordinate system, the axes are set up in parallel and equidistant to each other. A point in n -dimensional space is represented by a polyline crossing the n parallel axes. The position of the intersection on the j^{th} axis corresponds to the value of the j^{th} coordinate of the point. In the end each multidimensional point is represented by a polyline through the parallel axes. In the proposed approach parallel coordinates are used to initially classify fibers according to their individual characteristics. The number of fibers in a specimen ranges from several hundreds to hundreds of thousands and more and thus results in cluttering and occlusion. As too many lines are drawn between the parallel axes, the exploration process becomes very inefficient. Following the nested model for visualization design and validation [18] we examined our implementation and explored Axis Order Selection for parallel coordinates [19]. If axes representing fiber characteristics with hidden correlations are placed near to each other, the relationships between these characteristics are likely to become apparent. We then found that we will lose other potential correlations between the rest of the characteristics. After studying the coordinated parallel views for exploratory analysis of micro array time-course data [4], we took an approach which links a scatter plot matrix to enhance and refine the classification results of the PC.

4.1.2 Scatter Plot Matrix for Fibers

In addition to parallel coordinates a scatter plot matrix (SPM) [30] is used to visualize and reveal relationships such as dependencies, patterns and even outliers among all of the fiber characteristics. Additionally the scatter plot matrix serves as a refinement tool for the selection obtained using parallel coordinates. The scatter plot matrix used in our visualization pipeline consists of $n(n-1)/2$ scatter plots organized in a matrix. n represents the number of fiber characteristics used in the SPM. To avoid redundancy only the region below the main diagonal of the SPM is filled. A histogram of each fiber characteristic is shown in the main diagonal. Below this main diagonal a scatter plot is drawn for each pair of the characteristics. In the upper right corner an enlarged view of the selected scatter plot is displayed. In the enlarged view, and in the small charts as well, selections are done by drawing rectangles which will mark the selected data in red (*brushing*). These selections will be applied to all other scatter plots, the parallel coordinates as well as the 3D view (*linking*). In order to suggest initial classes of fibers a *k-means* algorithm [13] is used. The fiber characteristics depicted in the enlarged view are taken as input data for the automatic clustering. The total number of classes is specified by the user. Results of the classification can then be transferred to the *Fiber Class Explorer* or further refined in the parallel coordinates or the scatter plot matrix.

4.1.3 Fiber Class Explorer

The fiber class explorer lists all created classes of fibers and allows to add, modify or remove classes of interest. For each class the user may assign individual names and colors. In addition, for each class statistical information such as number of fibers (*Count*), the percentage of the fiber count (*Percent*), the *minimal*, the *maximal* and the *average* values of all fiber characteristics within a class are

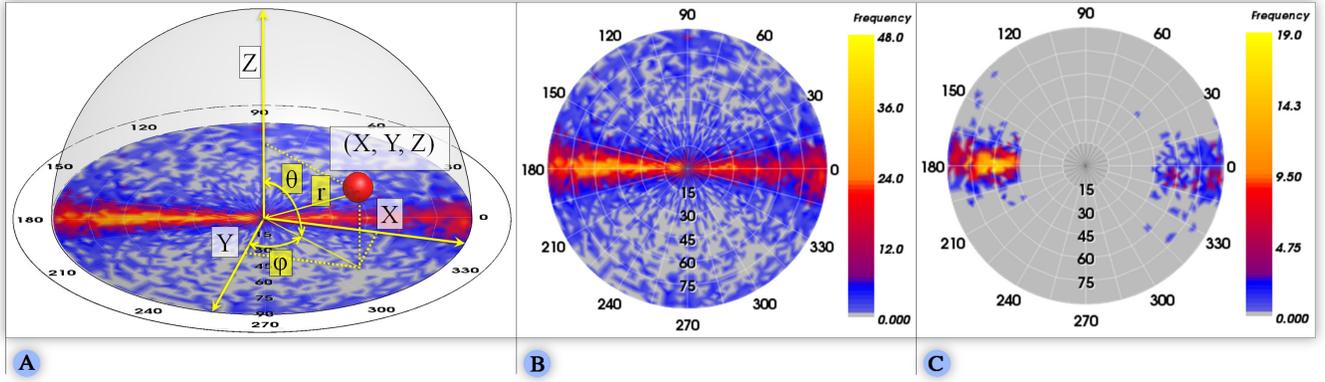


Figure 4: Fiber orientation distribution (FOD) in a PC plot. (A) Construction of the fiber orientations from Cartesian coordinates. (B) Global FOD (*dataset1*). (C) FOD of a single class (*dataset1*).

calculated. By clicking on a class of interest its elements are revealed and the individual properties of each fiber may be explored. It is also possible to check the 25 fiber characteristics individually. The checked features will be updated in the SPM and the PC immediately.

4.2 Fiber Orientation Distribution (FOD)

To visualize the fiber orientation, spherical coordinates are used. Figure 4A shows the construction of the fiber orientation from Cartesian coordinates. Here θ represents the polar angle measured from the zenith Z-direction. The azimuth angle φ lies in the XY-plane and is measured from the X-direction. Because of symmetry it is possible to depict all fiber orientations on a half sphere by specifying $\theta \in [0, \pi/2]$ and $\varphi \in [0, 2\pi)$. We discretize the northern half sphere with a user defined resolution and compute the frequency

of each discretized direction. This builds up the fiber orientation distribution (FOD). The azimuthal projection is later used to generate a 2D image of the FOD. Figure 4B depicts the global FOD of *dataset1*. The annotations around the outer circle represent the azimuthal angle and the annotations inside represent the polar angle. The color bar ranges from gray to yellow where gray encodes low frequency and yellow encodes high frequency. Gray is used to depict the orientations where no fibers are headed. In addition to the global FOD, we allow the computation of the orientation distribution for each manually defined class. The main orientations in both Figure 4A and Figure 4B are easily visible as yellow spots. A strong prevalence along the horizontal axis is present. The visualization of the FOD, which defines the mechanical loading capacity, is of great interest to the domain experts. We therefore applied a spherical color map (see Figure 5A) where the colors are mapped to the spatial fiber orientations. In order to highlight the X, Y and Z-direction of a dataset, we mapped these directions to red, green and blue respectively. Figure 5B shows a direct volume rendering of fibers by color coding the orientations with the spherical color map. This visualization allows easy identification of the fiber classes by their color.

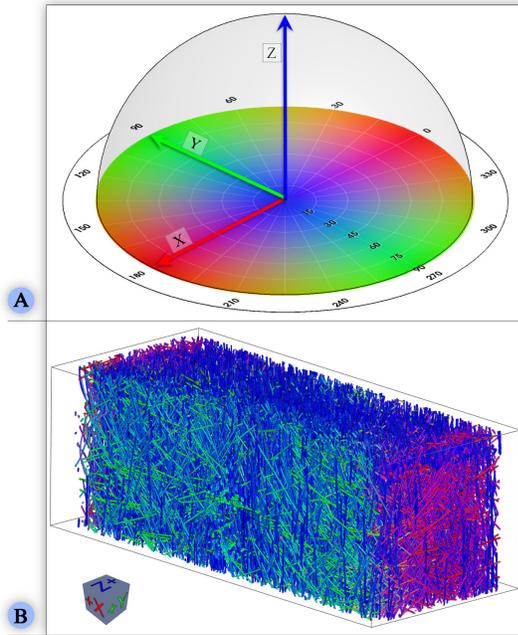


Figure 5: Visualization of the individual fiber orientations. (A) The spherical color map. (B) A direct volume rendering of the fibers using color-coded orientations (*dataset2*).

4.3 Fiber Length Distribution (FLD)

In addition to fiber orientation visualization, an automatic algorithm is applied to classify and visualize the fibers according to their length. The calculation of the fiber length distribution (FLD) is very important for the experts to quickly represent the layout of short or long fibers in the volume. Thus conclusions about the loading capacity of the material can be drawn. Figure 6A shows the 3D rendering of a fiber length distribution and Figure 6B shows the corresponding histogram.

4.4 Blob Visualization

For the domain experts, it is important to gain a quick overview of the shape of each fiber class and the layer structure in order to analyze the material build-up of the final component. Due to the issues of overlap and occlusion the separation of the different fiber classes is frequently problematic using techniques like direct volume rendering. This task is becoming challenging especially for datasets with a very high fiber density that contains thousands of fibers. Based on the defined fiber classes in the *Class Explorer* we introduce a blob visualization (see Figure 7) by applying methods of implicit modeling as proposed by Bloomenthal et al. [3].

A blob in our application case is defined as a closed contour surface surrounding all fibers of a class. It provides the domain experts with an enclosure of the class and shows the spatial location

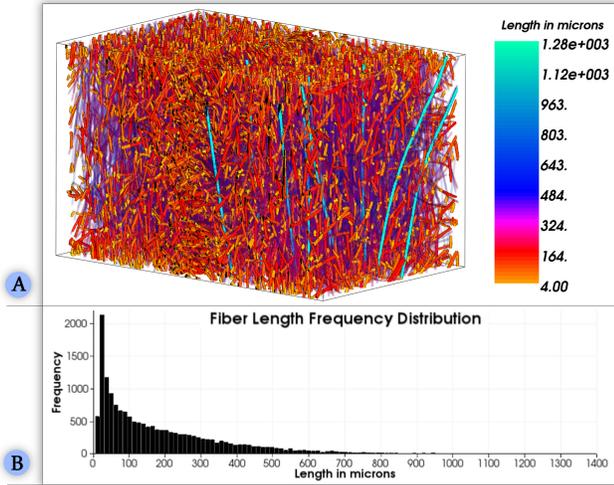


Figure 6: Visualization of the different fiber lengths. (A) 3D rendering of the fiber length distribution with the corresponding color map. (B) Fiber length distribution of *dataset1* shown in Figure 6A.

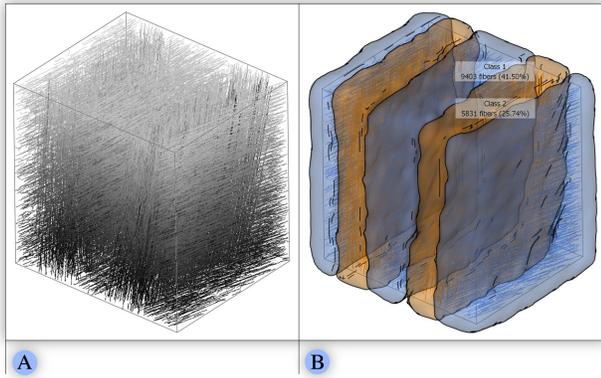


Figure 7: Blob visualization of *dataset3*. (A) 3D view of the dataset with unclassified fibers in gray. (B) 3D view of the blue and orange class with labeled blobs (*blue* Class 1, 9403 fibers (41.50%) and *orange* Class 2, 5831 fibers (25.74%)).

and shape of the class within the data. To construct the blob surface we apply a distance-field based approach which is remotely similar to the metaballs method proposed by Blinn et al. [2]. For every fiber of the class we specify a line segment so that the start and the end points of a line segment correspond to the start and the end points of a fiber. This provides an approximation for straight and slightly curved fibers. Taking all line segments we can define the shape of a blob by the following distance function defined in 3D space:

$$\min_{i=1..m} d_i \leq \text{threshold}$$

where m is the number of line segments, d_i is the Euclidean distance to the given line segment and threshold is a parameter defining the blob size. To obtain a mesh of the blob surface we uniformly sample the distance function on a grid and then apply the marching cubes algorithm [17] with a corresponding threshold value. In some cases blobs determined from different fiber classes may overlap, which results in unclear or cluttered representations. To solve this issue we have modified the algorithm in a way that it removes overlapping by adjusting the blob shapes (see Figure 7A and 7B). We resolve

conflicts for those points belonging to more than one blob using the following approach: the point belongs to the closest blob with the closest fiber. For all the other blobs we set the distance function to infinity so that they do not include the point. This way the point will belong to the blob with the closest fiber, and the areas where blobs overlap will become separated based on the corresponding Voronoi diagrams. We further allow the user to define the minimal distance separating any pair of blobs. If the minimal separating distance is introduced, the point in an overlapping area is not assigned to any of the blobs if the difference between their distance functions in this point is greater than the separation distance. Each blob in the 3D view is marked with a label containing the name of the class and short class statistics: the number of fibers in the class and the percentage from the total fiber count. In order to enhance the shape perception of the blob, the user can enable a silhouette rendering mode. This mode shows the outline of the blob and highlights its sharp edges using black lines.

4.5 Fiber Metadata Visualization

As described in Task 3, domain users need a method to explore the data in order to find regions of interest (ROI). Due to the high information content, visualizations based on the original volume data are often not efficient. In order to provide a higher level overview of the fiber characteristics' distribution in the data we use a fiber metadata visualization approach. We subsample the original volume data with a user specified scaling-factor which results in a meta-volume, i.e., a volume made up of larger cells, typically 5 to 20 voxels each. We then calculate local characteristic values based on the fibers which at least partially lie in each cell of the meta-volume. The average value of each fiber characteristic is calculated from all fibers of a cell. The individual fiber characteristics are used as input data for calculating the meta-volume. We visualize the meta-volume as a context for the original volume data in the 3D

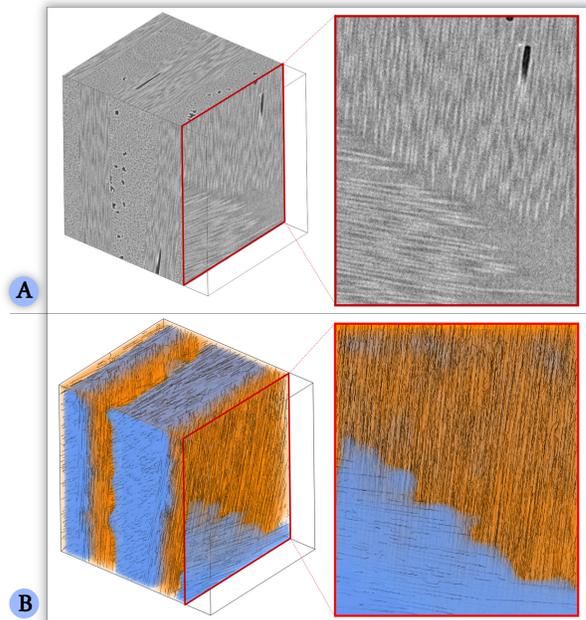


Figure 8: Fiber metadata visualization of *dataset3* in detail. (A) Left: 3D view of the original volume data set with a red border slice. Right: Slice view of the original dataset. (B) Left: 3D view of the meta-volume overlaid on the original volume data. Right: Slice view of the semi-transparent meta-volume overlaid on the original volume data with a linear blending.

view using multi-channel volume rendering (see Figure 8A) as well as overlaying in the 2D slice views. Figure 8B on the left, shows a meta-volume color coded according to the fiber orientation angle θ . An opacity indicator takes care of the overall adjustment regarding the opacity between the overlaid meta-volume and the original volume data in the slice views. Figure 8B on the right, shows the slice view of the meta-volume overlaid on the original volume data. The metadata visualization allows the user to pick a fiber characteristic of interest and to visualize the characteristic's distribution as a context. It enables a better visual exploration of the data by facilitating the identification of regions with similar or different fiber characteristics.

5 RESULTS AND EVALUATION

The generated results are demonstrated on different types of FRPs, i.e., one carbon fiber reinforced polymer and two glass fiber reinforced polymer specimens (see Section 5.1). A questionnaire to evaluate all presented methods was prepared and filled out by domain experts. The results outline the usability of the presented methods from the perspective of domain experts (see Section 5.2).

5.1 Visualization Results

Original Volume Data: As shown in in Figure 2 (input data), fiber classes or fiber orientations of *dataset1* are difficult to identify.

Visual Fiber Exploration Method: After the visual exploration process, the user is able to apply a multi-class rendering process to the manually defined classes. All fibers are colored according to their specific fiber class color in the parallel coordinates, scatter plot matrix and the 3D renderer. Figure 1 on the right and in the middle (blob visualization combined with multi-class rendering) depicts the manually defined classes for *dataset1*. All the classes can be clearly identified.

Orientation Identification: Figure 5 depicts the 3D view of the extracted fibers (*dataset2*) color coded according to the spherical color map (Figure 5A). The fiber orientations can be clearly identified. The color coding is applied to the 3D view and the 2D slices.

Fiber Length Distribution: An automatic algorithm is applied to classify and visualize the fibers according to their length. Figure 6 shows the color coding of the extracted fibers (*dataset1*) with respect to fiber length.

Blob Visualization: To provide the domain experts with an enclosure of all their defined classes, we applied the concept of blob visualization. This allows the domain experts to gain a quick overview of the specimens layer structure and the shape of the fiber classes. Figure 7 illustrates the blob visualization based on *dataset3*.

Fiber Metadata Visualization: A 3D view of the meta-volume (*dataset3*) color coded according to the fiber characteristic θ is shown in Figure 8 on the left. Orange represents a θ value between 0° and 10° and indicates that the fiber orientation is aligned to the Z-axis. Blue represents a θ value between 80° and 90° and denotes fibers which are aligned orthogonally to the Z-direction. The slice views (see Figure 8 on the right) with reduced opacity information clearly indicate a layer structure of the specimen.

5.2 Evaluation and User Feedback

The necessity of individual and interactive fiber visualizations originates from the requirement of non-destructive testing (NDT). During *FiberScout* development over a period of more than 18 months, improvements of the fiber visualization pipeline were constantly done together with the NDT practitioners. In order to get feedback on the *FiberScout* system, we designed an evaluation questionnaire with regard to the tasks defined by the domain experts (see Section 1). The questionnaire is structured so that the experiences of the participants with XCT are collected first. Then it is determined how suitable PC and SPM is for classifying the fibers. In addition,

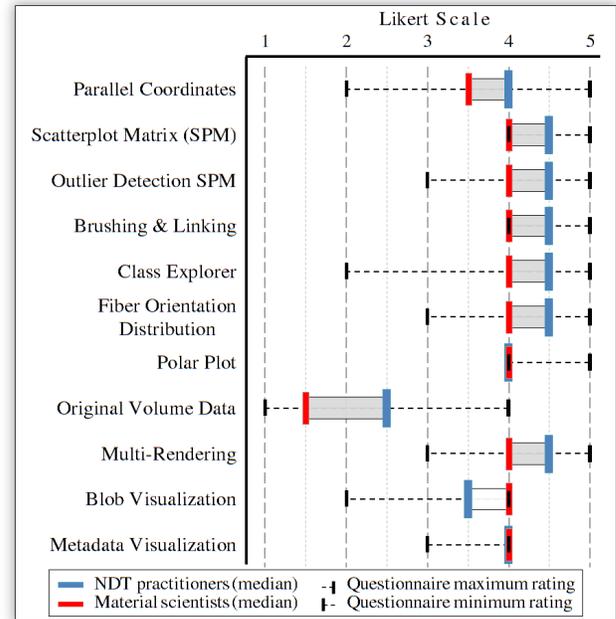


Figure 9: Averaged results of the evaluation questionnaire.

the usefulness of the statistical information of the fiber class explorer is determined. After that we tried to find out how the FOD is applicable for displaying fiber orientations. It is then checked if the fiber classes can be well distinguished by the blob visualization. Finally, it is determined how well metadata visualization suffices to indicate general fiber orientations. To evaluate the questionnaire we choose four NDT practitioners, who are familiar with X-ray computed tomography and its visual representations, and four material scientists, which are experienced in analyzing fiber reinforced polymers. The averaged and weighted results of the evaluation questionnaire are depicted in Figure 9. The red line represents the results of the material scientists while the blue one displays the results of the NDT practitioners. We use a Likert scale ranging from 1 to 5 to represent the user experience, varying from poor to excellent. The fiber visualization pipeline on the whole received good feedback from the domain experts. The SPM was considered as best suited for clustering fiber characteristics. By linking the SPM and PC the relationships between the fiber characteristics can be easily revealed. Outliers in the SPM are obvious to be detected. In addition the participants pointed out that further material phenomena such as porosity are easily observable. The orientation visualization is simple and self-explanatory. The main fiber orientation can be easily determined using the polar plot for the FOD. Both the NDT practitioners and the material scientists reckon that it is difficult to generate useful information of fiber characteristics using the original volume data. Blob and metadata visualization also provide valuable results for separating fiber classes. Furthermore, a difference in the results between NDT practitioners and material scientists is found in the outlier detection using the blob visualization. NDT practitioners perceive that it is obvious and simple to detect outliers, while the material scientists score this technique low.

6 SUMMARY AND CONCLUSIONS

We presented the *FiberScout*, a visualization system for the visual analysis of fiber characteristics in fiber reinforced polymers. The user feedback shows overall good results from domain experts, especially concerning clustering with the help of the SPM with *brushing & linking* and the visualization of the fiber orientation distribu-

tion. The metadata visualization allows the user to quickly explore the data and find regions of interest. The blob visualization is an appreciated technique to represent regions with the same characteristics in a volume. One shortcoming of the current implementation is that the analysis is limited to approximately 100.000 fibers. In case of one million fibers, the calculation times would last much longer. This fact could be counteracted by parallelizing appropriate code sections. Another problem relates to the PC and the SPM which are cluttered if too many fiber features are selected. For future work, the calculation of additional statistics and the selection of individual fibers in the 3D view can be mentioned. The experts indicated that combining the porosity information and the fiber characteristics of a specimen would be important for them in the future.

ACKNOWLEDGEMENTS

This project was supported by the QUICOM project, which is financed by the European Union Seventh Framework Programme (FP7/2007- 2013) under Grant Agreement n° 314562.

REFERENCES

- [1] H. Altendorf and D. Jeulin. 3D Directional Mathematical Morphology for Analysis of Fiber Orientations. *Image Analysis & Stereology*, 28(3), 2009.
- [2] J. F. Blinn. A Generalization of Algebraic Surface Drawing. *ACM Trans. Graph.*, 1(3):235–256, July 1982.
- [3] J. Bloomenthal and B. Wyvill. Interactive Techniques or Implicit Modeling. *SIGGRAPH Comput. Graph.*, 24(2):109–116, March 1990.
- [4] P. Craig, J. Kennedy, and A. Cumming. Coordinated Parallel Views for the Exploratory Analysis of Microarray Time-course Data. In *Proceedings of the Coordinated and Multiple Views in Exploratory Visualization*, CMV '05, pages 3–14, Washington, DC, USA, 2005. IEEE Computer Society.
- [5] L. Fritz, M. Hadwiger, G. Geier, G. Pittino, and M. E. Gröller. A Visual Approach to Efficient Analysis and Quantification of Ductile Iron and Reinforced Sprayed Concrete. *IEEE Transactions on Visualization and Computer Graphics*, 15(6):1343–1350, 2009.
- [6] S.-Y. Fu and B. Lauke. Effects of Fiber Length and Fiber Orientation Distributions on the Tensile Strength of Short-Fiber-Reinforced Polymers. *Composites Science and Technology*, 56(10):1179–1190, 1996.
- [7] H. Guo, H. Xiao, and X. Yuan. Multi-Dimensional Transfer Function Design based on Flexible Dimension Projection embedded in Parallel Coordinates. In *Proceedings of the 2011 IEEE Pacific Visualization Symposium, PACIFICVIS '11*, pages 19–26, Washington, DC, USA, 2011. IEEE Computer Society.
- [8] M. Hadwiger, L. Fritz, C. Rezk-Salama, T. Höllt, G. Geier, and T. Pabel. Interactive Volume Exploration for Feature Detection and Quantification in Industrial CT Data. *IEEE Transactions on Visualization and Computer Graphics*, 14(6):1507–1514, 2008.
- [9] C. Heinzl. *Analysis and Visualization of Industrial CT Data*. PhD thesis, Institute of Computer Graphics and Algorithms, Vienna University of Technology, 12 2009.
- [10] R. Huang, K.-L. Ma, P. McCormick, and W. Ward. Visualizing Industrial CT Volume Data for Nondestructive Testing Applications. In *Proceedings of the 14th IEEE Visualization 2003 (VIS'03)*, pages 547–554, Washington, DC, USA, 2003. IEEE Computer Society.
- [11] A. Inselberg and B. Dimsdale. Parallel Coordinates: A Tool for Visualizing Multi-Dimensional Geometry. In *Proceedings of the 1st conference on Visualization '90, VIS '90*, pages 361–378, Los Alamitos, CA, USA, 1990. IEEE Computer Society Press.
- [12] B. Jackson, T. Y. Lau, D. Schroeder, K. C. Toussaint, and D. F. Keefe. A Lightweight Tangible 3D Interface for Interactive Visualization of Thin Fiber Structures. *Visualization and Computer Graphics, IEEE Transactions on*, 19(12):2802–2809, 2013.
- [13] T. Kanungo, D. Mount, N. Netanyahu, C. Piatko, R. Silverman, and A. Wu. An Efficient k-Means Clustering Algorithm: Analysis and Implementation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 24(7):881–892, Jul 2002.
- [14] D. A. Keim. Information Visualization and Visual Data Mining. *IEEE Transactions on Visualization and Computer Graphics*, 8(1):1–8, 2002.
- [15] X. Kuang, H. Zhang, S. Zhao, and M. McGuffin. Tracing Tuples Across Dimensions: A Comparison of Scatterplots and Parallel Coordinate Plots. *Comp. Graph. Forum*, 31:1365–1374, June 2012.
- [16] B. Li, X. Zhao, and H. Qin. 4-Dimensional Geometry Lens: A Novel Volumetric Magnification Approach. *Computer Graphics Forum*, 2013.
- [17] W. Lorensen and H. Cline. Marching Cubes: A High Resolution 3D Surface Construction Algorithm. In *ACM SIGGRAPH Computer Graphics*, volume 21, pages 163–169, 1987.
- [18] T. Munzner. A Nested Model for Visualization Design and Validation. *IEEE Transactions on Visualization and Computer Graphics*, 15(6):921–928, nov.-dec. 2009.
- [19] H. Qu, W.-Y. Chan, A. Xu, K.-L. Chung, K.-H. Lau, and P. Guo. Visual Analysis of the Air Pollution Problem in Hong Kong. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1408–1415, Nov. 2007.
- [20] C. Red. Aviation Outlook: Composites in General Aviation 2011–2020. *High-Performance Composites*, May 2012.
- [21] K. Robb, O. Wirjadi, and K. Schladitz. Fiber Orientation Estimation from 3D Image Data: Practical Algorithms, Visualization, and Interpretation. In *Proceedings of the 7th International Conference on Hybrid Intelligent Systems, HIS '07*, pages 320–325, Washington, DC, USA, 2007. IEEE Computer Society.
- [22] D. Salaberger, K. A. Kannappan, J. Kastner, J. Reussner, and T. Auinger. Evaluation of Computed Tomography Data from Fibre Reinforced Polymers to Determine Fibre Length Distribution. In *International Polymer Processing*, volume 3, pages 283–291, 2011.
- [23] B. Shneiderman. The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. In *Proceedings of the 1996 IEEE Symposium on Visual Languages, VL '96*, pages 336–343, Washington, DC, USA, 1996. IEEE Computer Society.
- [24] J. Sloan. Carbon Fiber Market: Cautious Optimism. Composites world (accessed on 02.09.2013 18:37), 3 2011. <http://www.compositesworld.com/articles/carbon-fiber-market-cautious-optimism>.
- [25] M. Stommel, M. Stojek, and W. Korte. *FEM zur Berechnung von Kunststoff- und Elastomerbauteilen*. Carl Hanser Verlag, 2011.
- [26] A. Tatu, F. Maas, I. Farber, E. Bertini, T. Schreck, T. Seidl, and D. Keim. Subspace Search and Visualization to make Sense of Alternative Clusterings in High-Dimensional Data. In *IEEE Conference on Visual Analytics Science and Technology (VAST)*, pages 63–72, 2012.
- [27] M. Teßmann, S. Mohr, S. Gayetsky, U. Hassler, R. Hanke, and G. Greiner. Automatic Determination of Fiber-Length Distribution in Composite Material using 3D CT Data. *EURASIP J. Adv. Signal Process.*, 2010:1:1–1:9, Feb. 2010.
- [28] C. L. Tucker and E. Liang. Stiffness Predictions for Unidirectional Short-Fiber Composites: Review and Evaluation. *Compos Sci Technol.*, 59:655–671, 1998.
- [29] VGStudioMAX. VolumeGraphics - VGStudioMAX 2.2. <http://www.volumegraphics.com/>, 2013.
- [30] P. C. Wong and R. D. Bergeron. 30 Years of Multidimensional Multivariate Visualization. In *Scientific Visualization, Overviews, Methodologies, and Techniques*, pages 3–33, Washington, DC, USA, 1997. IEEE Computer Society.
- [31] B. Yamrom, J. A. Sutliff, and A. P. Woodfield. Visualizing Polycrystalline Orientation Microstructures with Spherical Color Maps. In *Proceedings of the conference on Visualization '94, VIS '94*, pages 46–51, Los Alamitos, CA, USA, 1994. IEEE Computer Society Press.
- [32] X. Zhao and A. Kaufman. Multi-Dimensional Reduction and Transfer Function Design using Parallel Coordinates. In *Proceedings of the 8th IEEE/EG international conference on Volume Graphics, VG'10*, pages 69–76, Aire-la-Ville, Switzerland, 2010. Eurographics Association.
- [33] H. Zhou, W. Cui, H. Qu, Y. Wu, X. Yuan, and W. Zhuo. Splating the Lines in Parallel Coordinates. *Comput. Graph. Forum*, pages 759–766, 2009.