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Visualization of Fiber Orientation in Glass Fiber Reinforced Polymers

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Danksagung

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Kurzfassung

Zur Herstellung von Leiterplatten, Eisenbahnschwellen, Flugzeugen oder Formel-1-Wagen, werden Materialien verwendet, welche ganz besondere Eigenschaften aufweisen müssen. Zudem ist die Qualität dieser Materialien besonders wichtig. Die Rede ist von Faserverbundwerkstoffen. Diese treten in unterschiedlichen Varianten auf. Von kohlenstofffaserverstärktem Kunststoff bis hin zu FFU-Kunstholz (aus dem englischen Fiber Reinforced Foamed Urethane). Um diese Materialien, genauer gesagt die Fasern aus denen diese bestehen, genauer zu überprüfen, werden unterschiedliche Methoden verwendet. Eine Möglichkeit ist es, das Material mit einem Computed Tomography (CT) Scan als volumetrisches CT-Bild auf einem Computer zu speichern. Daraufhin kann mit diesen Daten gearbeitet werden, um mögliche Brüche oder auch andere Strukturen darin zu erkennen. Im Falle dieser Arbeit wird eine Software entwickelt, welche später in ein Programm namens open_iA integriert wird. Ziel dieser Software ist es, die Orientierung von Fasern zu erkennen und diese durch eine Visualisierung bestmöglich darzustellen. Besonders interessant ist es, anhand von unterschiedlichen Einstellmöglichkeiten diese Visualisierungen noch spezifischer zu gestalten, wodurch es möglich ist, einen besonders genau Einblick in den Werkstoff zu bekommen.

Abstract

Fiber-reinforced composites are materials used for their extraordinary characteristics. The importance of these materials is constantly increasing, therefore, a wide range of variations exists of this material. Types range from Carbon Fiber Reinforced Polymer to Fiber-reinforced Foamed Urethane and more. Fiber-reinforced composites are lightweight, strong, and durable, among others and are therefore used for printed circuit boards, railway sleepers, airplanes or Formula 1 vehicles. To assure that these materials provide the required quality, they need to be tested and analyzed. To analyze these materials or to be more exact, the fibers within, special tools are needed. The first step is to scan the material with a X-ray Computed Tomography (CT) and save it as a volumetric CT-image on a computer. Now this data can be used to analyze the structure and find flaws in the dataset. In this thesis, a program for a later integration in a software called open_iA to extend its range of features, is developed. Purpose of the developed program is to analyze the orientation of fibers in a dataset. The result will be visualized with two different graphs. One shows the orientation of the fibers, while the other shows how many fibers are visible to the analyst. With the option of different configurations, it is possible to further specify these visualizations and get a better understanding of the underlying data.

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CHAPTER 1

Introduction

Fiber-reinforced composite is a composite material combining two and more components. Typically these components are polymer matrix and fibers. The fibers can be glass, basalt, carbon or aramid. In Figure 1.1 a scan from a X-ray CT machine can be seen, which should help getting an idea of the internal structure. Fiber-reinforced plastic in comparison to traditional materials is a really strong, and still lightweight material which makes it useful for all different types of applications. One of the most known fibers is the carbon fiber. It is used for bikes, cars, airplanes, and many other products. For example, BMW uses 12% mineral-filled elastomer modified polypropylene (PP) compound material in its newest electric car series. [Bor] The material is lightweight but also robust, therefore these properties are optimal for electric cars to improve their speed and range. Beside the listed properties it also fulfills BMW's paint adhesion quality requirements.

Depending on the requirements of the product multiple fiber reinforced materials can be used in a single product. BMW also uses more than one composite material for their electric cars. Another material used by BMW is a 20% long glass fiber reinforced PP. It provides great strength and high stiffness. Not only BMW uses these sorts of materials. Also, Mercedes utilizes the great characteristics of fiber-reinforced materials. [HH06] There are a lot more manufactures using these materials for their products.

The manufacturing process of composite materials is challenging and might lead to faults in the final product. Even if the finished product seems flawless, there can be defects that are not visible to the human eye. For some applications this can be ignored, but for critical application like it is the case with aeronautic, the fibers need to be flawless. In order to achieve this, it is needed to analyze the structure of the fibers for fractures and other errors. This is not an easy task, microscopes and other expensive machines are needed to get insight into the materials. Figure 1.1 shows the result acquired from a X-ray CT machine used on a fiber reinforced polymer material. Even if the structure is now observable, the whole material still needs to be strictly analyzed to find every little flaw in its structure. Through computers and their always increasing processing power, it

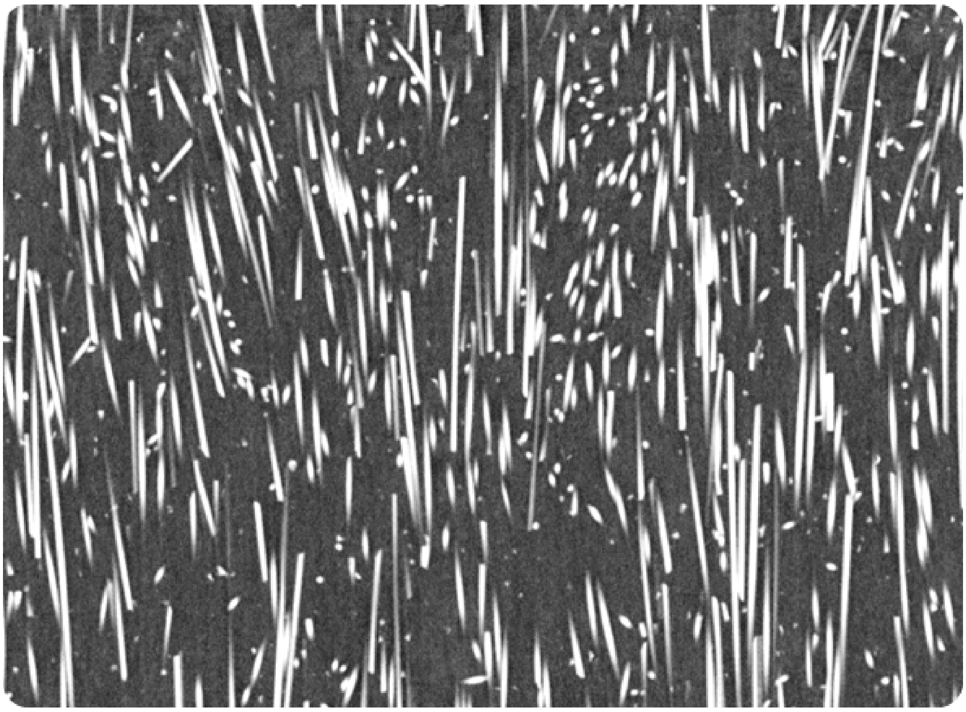

Figure 1.1: Scan of a glass fiber reinforced polymer material acquired through the use of a X-ray CT machine.

is possible to develop new methods for getting a better insight into the structure of the material, and furthermore this results in a better quality control and also higher quality end-results.

1.1 Motivation

The motivation is to improve the quality of fiber based materials through a better insight into their structure and characteristics. Domain experts are interested in visual analysis of fiber characteristics such as direction and amount of fibers. To facilitate this, certain machines and tools are needed. The better the tools for analytical tasks become in this domain, the easier it gets, to push this materials to their limits. The first step would be to developed a software which helps to explore and find regions of interest. Subsequently characteristics of the material like the orientations of the fibers can be visualized together with another visualization for the amount of visible fibers.

1.2 Goal of the Thesis

The goal is to develop an approach to visualize fiber constellations using different techniques. This should help to get a better understanding of the underlying dataset.

Though some datasets can contain over thousands of fibers, it should be possible to isolate some of them to provide a better overview. This is possible through adjusting certain parameters and also depends on the users viewing angle on the 3D mesh. It is also possible to turn on arrows which are painted on top of the fibers. This should make it easier to see which fibers are currently considered for analysis and also to get a better understanding of the orientation. The final part is to show the orientation of the selected fibers in a scatter plot. A second plot shows how many fibers are visible from the user's perspective. This number depends on how much of the surface of each fiber is visible to the camera.

1.3 Structure of the Work

At first it is needed to take a closer look at the procedure of capturing the dataset for further analysis. It is important to understand how fiber-reinforced composites are structured to create a suitable analytical solution. The next part is about the implementation of the functionality. All details about the used visualizations and the orientation finding algorithm is part of this section. The last part will be the evaluation. It is important that the results are accurate and can be used in the real world. The evaluations of the developed visualizations are also part of this section.

CHAPTER 2

Background

2.1 Composite materials

A composite material is a material which is made from two or more different materials. Fiber-reinforced plastic is also one of these composite materials which is made of a polymer matrix reinforced with fibers. The fibers are usually glass, carbon, aramid, or basalt. Paper, wood and asbestos have also been used. The goal is to create a material with characteristics different from each of the combined materials. Inside the composite material the individual components are still separate. The result should be a material which is lighter, stronger and cheaper than any comparable traditional material.

Composite materials can include metal, mortars, concrete, plastic, ceramic, carbon, glass, aramid and even wood. They can be used for cars, buildings, interior, sports products and motorways to name just a few. The most complex and critical use case for composite materials is the spacecraft and aircraft industry. [MSOTS14] In this area all the materials need to be fully optimized and the stronger and lighter they are the better.

To create composites, constituent materials are needed. There are two types of constituent materials. They are called matrix and reinforcement. Both types need to be present to create a composite material. The matrix surrounds the reinforcement material and keeps it in place. [Jan03b][Jan03a] The graphic in Figure 2.1 shows the structure of the composition.

2.2 Testing of Fiber-reinforced materials

To predict and prevent failures of the material, it is essential to analyze the material. There are different ways to get insight into its internal structure. One strategy is to cut apart the material, which is not always desired because it can alter the original attributes and structure. Another way is with the use of a machine which scans the material and

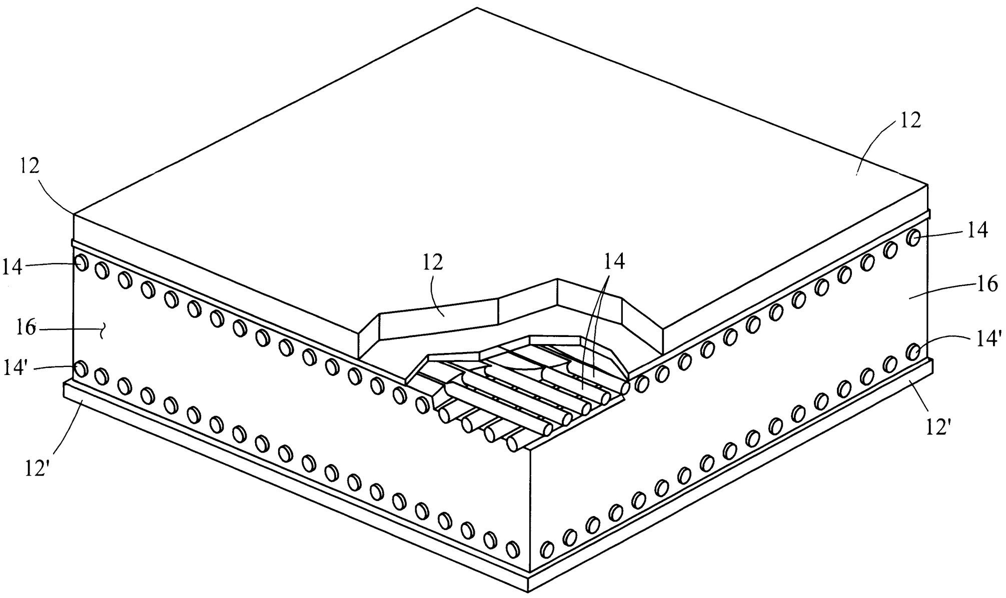

Figure 2.1: Composite material with outer layer(12), the reinforcement(14) and the matrix(16) part. [OKS+01]

creates a dataset for further examination. This method is not always cheap as special machines and computer-software are needed. [Gho16] [MSOTS14]

2.2.1 Destructive Testing

The quickest and most likely cheapest method to test a composite material is through a destructive way. With this method, the material gets decamped or peeled layer for layer in order to get an insight. Microscopes are used to analyze the structure and condition of the fibers. Through this approach it is possible to get high-resolution images from the inside of the material. The downside is, because of the cutting process the material can be changed. As a result the data of the analysis can be distorted because of the impact of the exposure process. On top of that the material cannot be used for further testing because of the damage done to it. Using non-destructive testing instead of the destructive method can prevent these consequences.

2.2.2 Non-Destructive Testing

To analyze the material without doing any physical damage to it, the material can for example be scanned by a x-ray machine. Another technique would be ultrasonic inspection. This is a contact method which uses very short ultrasonic pulse-waves with center frequencies ranging from 0.1 to 50 MHz. These waves are transmitted into the

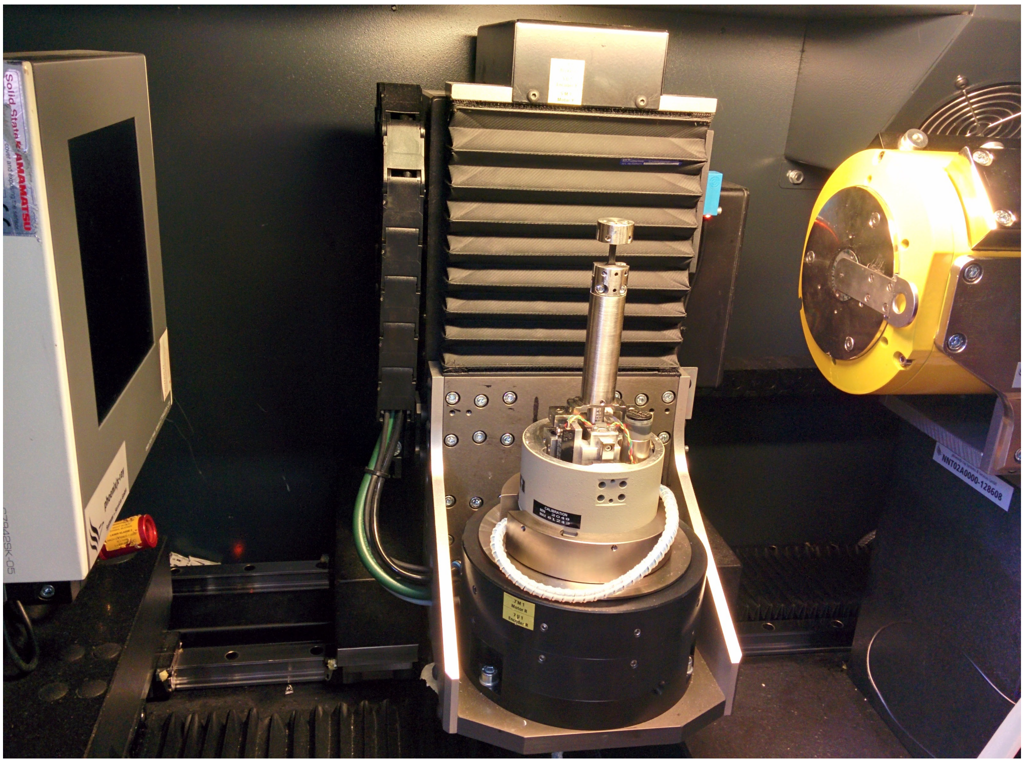

Figure 2.2: Industrial Computed Tomography machine with the name Nanotom

material to detect internal flaws. There are other non-destructive testing techniques which can be further split up into Contact and Non-Contact Methods. Contact Methods require direct contact between the sensor and the composite surface to obtain reliable data, while Non-Contact Methods work without contact. Some of these Non-Destructive Contact and Non-Contact Methods can be found in the Table 2.1 below. [Gho16]

Table 2.1: Non-destructive testing methods divided into two groups

Contact Methods	Non-Contact Methods
Traditional ultrasonic testing	Through transmission Ultrasonic
Eddy current testing	Radiography testing
Magnetic testing	Thermography
Electromagnetic	Infrared testing
Penetrant testing	Holography
Liquid penetrant	Shearography
-	Visual inspection

The dataset for this thesis is generated with an industrial Computed Tomography (CT). This is a Non-Destructive approach and falls in the Non-Contact category. The CT scans the material and creates a digital copy of it. In Figure 2.2 a picture of the machine used for the scan process can be seen. After the process is over, the result is a volumetric CT-image which can be used for further investigation with programs like VG Studio [VG], Avizo [Avi] or as it is the case in this paper open_iA [ope]. After the dataset is loaded into the program, the analysis for flaws and other characteristics can begin. The big advantage compared with the destructive approach is, that it is now possible to go inside and also back outside of the material without further effort.

2.3 open_iA

Open_iA is a program with the purpose to analyze fiber-reinforced materials. The program of this thesis, which is later included into open_iA, is written in C++ with the software framework QT [QT]. This also applies to open_iA. OpenGL is used to represent the 3D Data. This allows the user to run the application on any x86 and x64 hardware which supports QT and OpenGL.

CHAPTER 3

Implementation

3.1 Overview

In Figure 3.1 the Graphical User Interface of the program used for the implementation of this thesis can be seen. The 'Load from File' button is used to load the data from the dataset which should be analyzed. The left portion of the GUI shows the 3D representation of the loaded dataset. With the mouse it is possible to rotate the object. On the right side it is possible to choose between two different visualizations. One for the orientation of the fibers and one for the visibility. These visualizations can be configured through buttons and text inputs . At the bottom is the console which shows informations

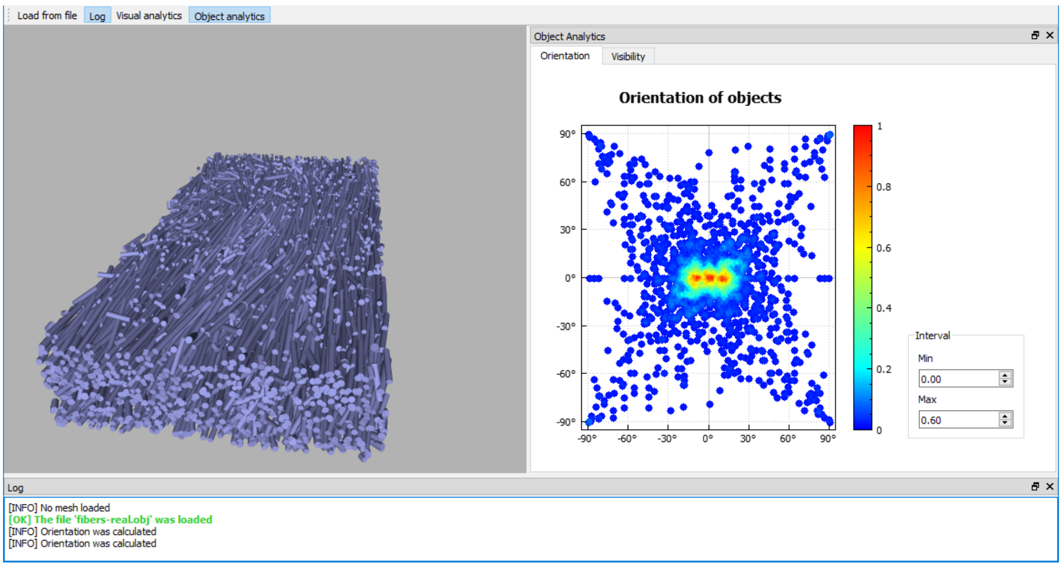

Figure 3.1: GUI with the main window on the left and the analysis panels on the right.

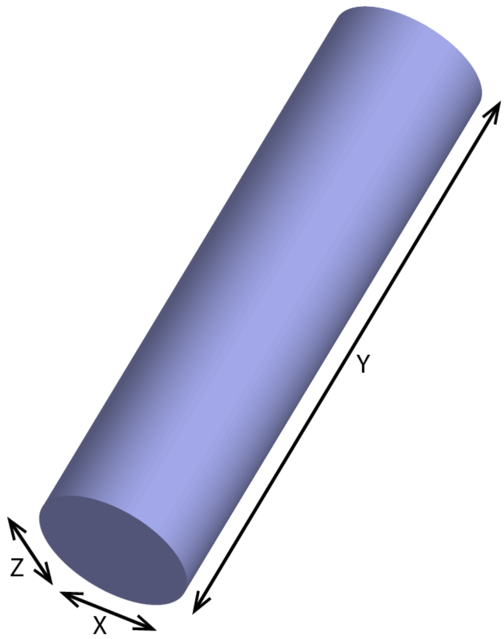

Figure 3.2: The longest of the three sides is the orientation of the fiber. In this example it would be the direction of the line labeled with 'Y'.

and errors of the program. All of the sub-windows except the main window, which is used to renders the raw mesh, can be hidden or separated from the main window.

3.2 Orientation finding algorithm

The algorithm for finding the orientation of each fiber is a crucial part of the implementation. Most of the other parts of the implementation build up on these results. If the results of the algorithm are wrong all the dependent parts are also wrong. The orientation of a fiber is defined as the direction in which the longest side of the fiber is facing. A visualization can be seen in Figure 3.2. For each fiber in the mesh, the algorithm starts off by finding all its vertices. Now the distances between all vertices are calculated and sorted in a descending order. Starting from the first entry, the algorithm picks the two vertices of each length which are not already picked. For the first picket length, the two corresponding vertices are added to one group each. For all the additional entries in the list, the algorithm decides which one of the two vertices is closer to the mean position of one group and adds it to the group. The other vertex is added to the other group. Ones all the vertices are classified to one of the two groups, the mean positions from all the vertices in each group are calculated. From these two resulting points, the direction can be calculated through subtracting one from the other. The direction vector is now normalized and added to the list of orientation vectors. Algorithm 3.1 shows the pseudo code of the implementation.

Algorithm 3.1: Orientation finding algorithm for a mesh

Data: the mesh containing all fibers

Result: direction list with direction vector for each object in the mesh

```
for object in mesh do
    verticesList;
    lengthList;
    for vertex in object do
        verticesList.add(vertex);
    end
    for v1 in verticesList do
        for v2 in verticesList do
            lengthList.add(v1, v2, distance(v1,v2));
        end
    end
    sortDescendingDistance(lengthList);
    lengthListReduced;
    for length in lengthList do
        if length.vertices not in lengthListReduced then
            lengthListReduced.add(length);
        end
    end
    group1;
    group2;
    for length in lengthListReduced do
        if length.v1 closer to mean(group1) then
            group1.add(length.v1);
            group2.add(length.v2);
        else
            group1.add(length.v2);
            group2.add(length.v1);
        end
    end
    direction = mean(group1) - mean(group2);
    directionList.add(direction);
end
```

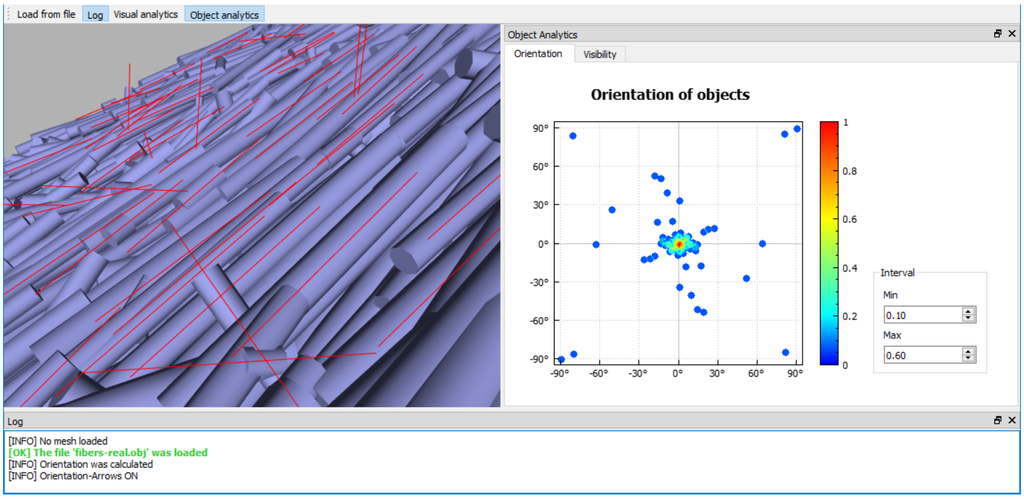

Figure 3.3: Red lines in the main view show the directions of the fibers, the scatter-plot shows the direction of the fibers in degree.

3.3 Orientation visualizations and graphs

For the analytic representation of the data, two graphs needed to be implemented. The first one is for showing all the orientations of all the fibers in the mesh at once. The second one is used for showing how many fibers are visible to the user based on the amount of surface of each fiber visible to the user. A more detailed description of each graph will be in the next subsection. Another functionality is, that the graphs are interactive so they change based on the configuration or when the viewing position changes. When the implementation started, the QT plot library was used. The customization limits of the library were quickly reached, still results were not satisfying. In order to design the plots the way they were needed to be, a library called QCustomPlot [QCu] was used. Basically, this library builds up on top of the implementation of the QT plot library. With this library, most of the needed functionality could be provided, but there were still some problems with it. In order to get the graphs exactly the way they were planned, some of the functionalities of QCustomPlot needed to be overwritten.

3.3.1 Orientation plot

The idea is to draw a scatter plot with two angels from -90 to 90 degrees each. In the case of multiple fibers having the same direction a color scale is added to the right side of the graph. Without this technique it would not be possible to perceive how many fibers are facing in the same direction, which drastically reduces the quality of the visualization. If there are 100 fibers facing in the same direction, they would still appear as one point in the visualization and in order to tackle this problem the color scale is added to the scatter plot. The more fibers are facing in the same orientation, the more the color changes depending on the color scale. This is in relation to the maximum number of

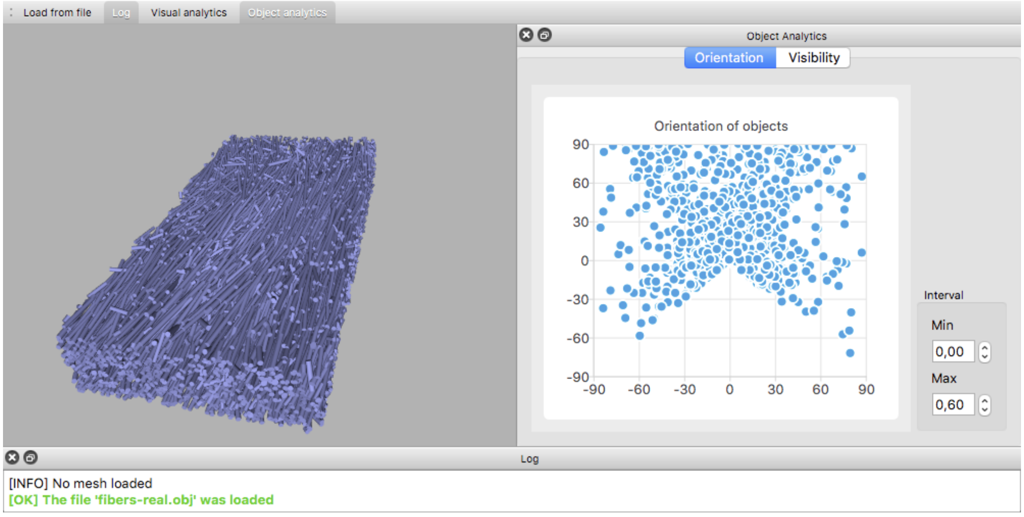

Figure 3.4: Implementation with disabled density informations of the orientation visualization.

fibers facing in the same direction. For example, if there are 10 fibers facing in the same direction, which is the maximum of fibers facing in the same direction, this group is shown with the max color from the color scale. If a second group has five fibers facing in a direction which is different from the previously mentioned direction, the color will be from the middle of the color scale.

The QT Plot Library can not be equipped with a color scale which made it impossible to design the graph the way it was planned. Followed by this realization another graph library was used. QCustomPlot has more customization possibilities than the standard QT Plot library. Still to get the color scale to work with the scatter plot some draw methods of the class QCustomPlot needed to be overwritten. The result can be seen in Figure 3.3. On the right side of the graph there are two numeric input fields, which can be used to set an interval and change the fibers which are considered for the visualization. This value corresponds with the amount of surface of each fiber visible to the user. In Figure 3.4 an old implementation of the orientation visualization can be seen. As described each fiber is one dot and if multiple fibers have the same orientation they would overlap each other.

In addition, with the button press 'O', it is possible to toggle an overlay of arrows in the main view. Only the fibers which are considered in the chart are getting marked with an arrow. These arrows point in the calculated direction of each corresponding fiber.

3.3.2 Visibility plot

This plot shows the amount of visible fibers to the user. The graph used for this visualization is a bar chart and each bar shows how many fibers are visible in each

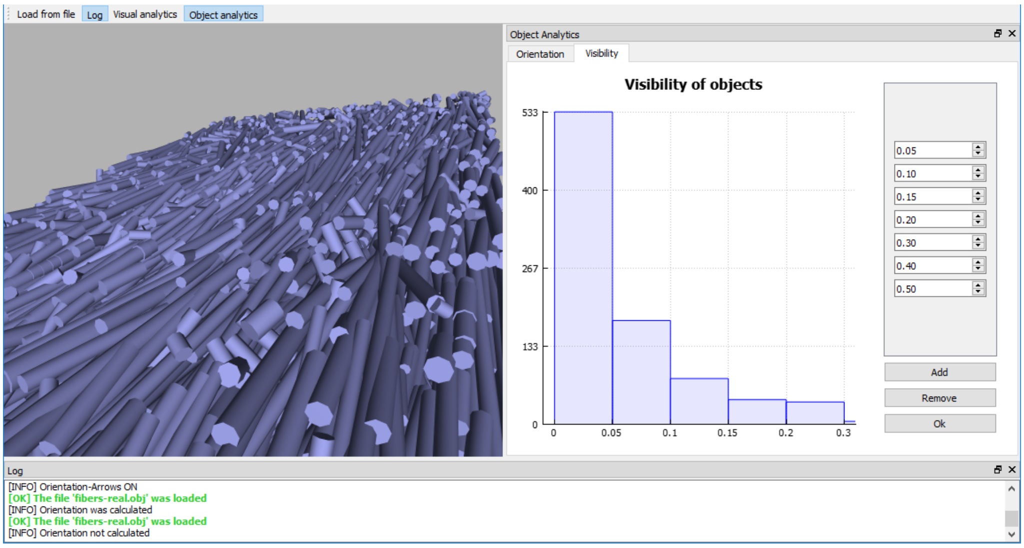

Figure 3.5: Number of visible fibers based on the configured interval

interval. The interval can be changed with the input fields on the right side of the graph as seen in Figure 3.5. It is possible to add, remove or change interval limits. The value for the classification is based on the amount of area of each fiber visible to the user. When the viewing angle changes the graph also changes in real time. This functionality can be used to analyze only certain fibers which are fully visible to the analyst. It can also be useful to find the amount of fibers which fulfill the adjusted interval.

CHAPTER 4

Evaluation

After the functionality is implemented, it is also needed to evaluate the results, otherwise it is not possible to be certain about the correctness of the results. For a quick control of the calculated orientations, the user can turn on the orientation arrows. Now a red arrow is drawn on top of each fiber showing its orientation and can be used as a visual check of the calculation. In addition the results from the orientation algorithm were also compared to the ground truth of a test dataset.

4.1 Orientation finding error rate

The 3D meshes used for this thesis are generated from excel sheets, which were acquired from real scans of fiber reinforced materials. To check how accurate the calculated orientations are, it is needed to compare them with the values in the excel file. The direction vectors from the excel file were compared to the calculated direction vectors from the mesh through the use of the dot product. If the resulting value from each fiber equals 1.0, the directions are identical. If the value is 0.0, the two directions are in a square angle to each other. The tested dataset contained 1485 fibers. 1481 fiber orientation were calculated completely correct, with just four orientations wrong. The average error for all angels was 0.1643 degrees. The reason for some direction vectors to be not correct is the width/length ration of some fiber.

As mentioned in a previous chapter, the orientation of a fiber is its longest side. This definition can be tricked based on the characteristics of the fiber. There is one special case where it can happen that the algorithm calculates the orientation of a fiber wrong. The reason for this to happen is not the algorithms fault itself, but more due to the characteristics of the fiber. If the fibers length is greater than the width of the fiber, the results are mostly correct. When it is the other way around, the algorithm detects the width as its longest side, and sets the orientation accordingly, which results in a wrong

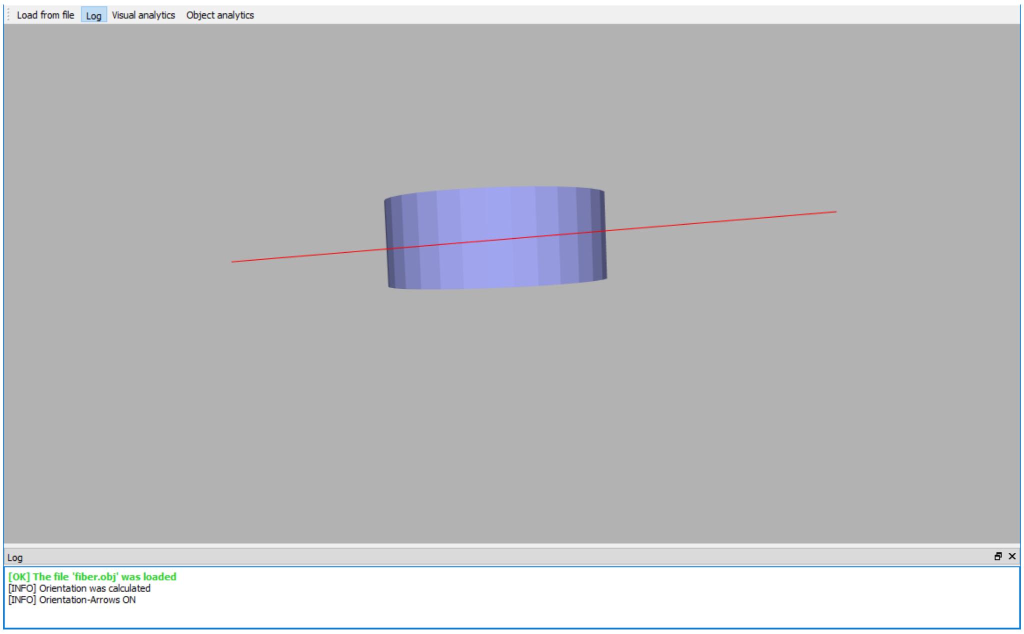

Figure 4.1: A short fiber with width/depth > length.

result. A visualization of the problem can be found in Figure 4.1. It is hard to prevent this from happening because from a logical point of view, it is a correct result.

4.2 Presentation of the plots

All the points in the orientation graph are also shown with arrows in the main view. Based on these arrows it is possible to visually verify the correctness of the calculated directions. The points in the graph are directly linked to the direction vectors of each fiber. If the data shown in the orientation graph is wrong, it is most likely due to a wrong calculation of the orientation vector. The graph for the visibility does not depend on the orientation of the fiber but on how much of each fiber is visible to the user. This graph is easier to double check because the user can count the visible fibers on the screen and compare them with the numbers in the graph.

4.3 Program stability

The ram memory usage of the program is stable. After monitoring the program for some time, no memory leaks could be detected. The programs ram usage depends on the size of the dataset that is loaded. It starts from around 50 MB when no dataset is loaded, up to around 300 MB with the biggest for this thesis available dataset which contains around 6000 fibers. For datasets this big, the time to load the dataset itself, and the calculation of the orientation takes some time. During this period, the program is not usable, but the loading events can be canceled at any time. When a big dataset is loaded, the program can start to stutter, but this depends on the processing power of the CPU (central processing unit) and also GPU (graphics processing unit) of the used computer.

CHAPTER 5

Conclusion

The final achievement of this thesis is the finished implementation of a functionality for finding orientations of fibers in a fiber-reinforced material. The algorithm for finding the orientation of all the fibers is the core component of the implementation. Therefore, the results of the algorithm were tested against the ground truth of the dataset to provide a high accuracy. Two graphs are used for the visualization of the calculated data. It is also important to differentiate the result of this thesis, from the ongoing impact this functionality can have on research and analysis of fiber compound materials.

The implementation overall was trouble-free. There were some changes over the time of the implementation. For example, the algorithm for finding the directions of the fibers was changed several times. Also, the way the data is presented through graphs evolved over the course of the implementation in order to find the best possible solution. It was difficult to design the graphs the way they suit the underlying data best, but after some different approaches the graphs could be designed in a way that they offer a satisfying insight into the loaded dataset.

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