Interactive Exploration of Flow Fields Using Commodity Hardware

A thesis submitted in partial fulfillment for the
degree of Master of Science

by

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Abstract

Flow visualization is a widely-used technique to explore flow fields, which occur in many different research areas. Until now these visualizations are usually performed in traditional desktop settings. But the emergence of tablet PCs offers new possibilities in terms of user interaction. Additionally it facilitate new ways to incorporate flow visualizations into the work process.

The aim of this project is to examine the potential and limitations of tablet PCs for flow field visualization. Therefore two flow field visualization apps for iPads are created, one standalone and one client-server system. These applications are equipped with common visualization techniques and utilize the tablet PC's specific user interaction methods.

Furthermore the apps are tested with technical performance tests and a user study. The results show that the applications in general received very positive responses from the test-users. Some interaction methods need to be improved, but overall they were perceived as intuitive and easy to understand. Moreover the standalone version performed surprisingly well in the technical tests. The client-server app proved to be a good extension in terms of reducing the processing time.

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Chapter 1

Introduction

The exploration and analysis of flow fields is part of many research areas. That includes for example the examination of the circulation around vehicles, aircraft or vessels, the observation of atmospheric flow for the weather forecast or the analysis of the characteristics of fluids in technical facilities. The flow data can result from measurements as well as from simulations. For a long time researchers use the techniques of flow visualization for the interactive exploration of these flow fields. The visualization plays an important role in the efficient analysis and communication of the characteristics of flow datasets.

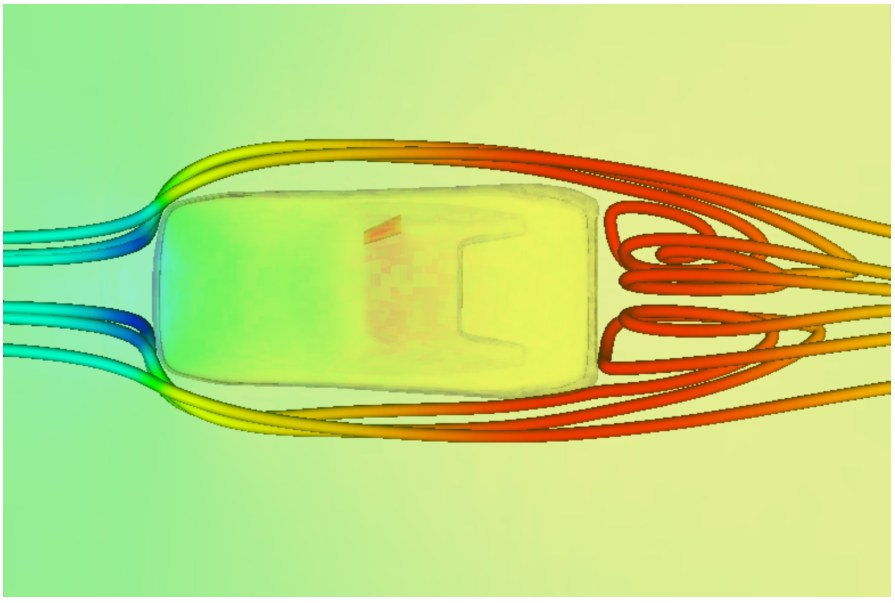


FIGURE 1.1: A visualization of a flow field resulting from numerical simulations with a car model.

So far these visualizations are usually performed in traditional desktop settings. But the emergence of tablet PCs and their availability in typical office environments, provides some interesting new possibilities. First of all tablet PCs offer new ways of user interaction such as touch gestures or the use of the gyroscope. Additionally the mobility and wireless use open up new ways of incorporating visualizations into the work process. The tablet PC can easily be brought along to meetings, factory workshops or ward rounds

in a hospital. Thus collaboration and communication could be improved by using tablet PCs.

In this project the suitability of interactive exploration of flow fields on tablet PCs should be examined. That includes the evaluation of the user interaction techniques with regard to flow visualization. Moreover the limitations of the hardware should be studied.

In order to achieve these goals, a system for interactive exploration of flow fields will be created. The hardware platform will be a tablet PC with touch and gyroscope sensors.

1.1 Related Research

So far it has been established that the new interaction possibilities offered by tablet PCs can enhance the user experience. Especially the touch interface has received good response. In 2011 Isenberg discussed the use of direct-touch interaction in scientific visualization in a position paper [Isenberg11]. He closes his review of related work with the conclusion that direct-touch interaction could enable the use of scientific visualization in many different display and user settings. Moreover this technique could be useful in the exploration process, facilitating a discussion or the collaborative creation and manipulation of scientific data.

In contrast to touch gestures, the success of interaction methods based on the gyroscope depends heavily on the application. In 2004 Eißele et al. [ESWE04] examined an augmented reality system on a mobile device, for which the user interaction was based on inertial orientation sensing. They developed five different interaction methods in three different application scenarios. The first application is an AR explorer that displays a virtual object, with additional information, at the same location and orientation as the real world object. The inertial sensor was used to navigate and rotate the view of the object. Furthermore vertical tilt gestures could also be used to select different parts of the virtual object, which then could be modified with horizontal tilt gestures. Additionally the inertial sensor was utilized to scroll through text or a website in two different application settings. At last a marble game was developed, in which the marble was steered by tilting the device.

The different interaction methods were evaluated with a small user poll with seven participants, which tested four aspects: handling, advantage, precision, intuitively usable. The ratings varied for the different applications and methods. Scrolling in texts for example was perceived well in terms of handling, precision and as very intuitive to use. For websites, which included hyper-links, the reactions were rather negative. Overall the gaming application received the best ratings overall and was the only one that received a 'very good' for its precision.

Other research on utilizing the inertial sensors of mobile devices mainly focuses on game-related applications or virtual reality. For example Hürst and Helder [HH11] examined different 3D visualization concepts for 3D games and virtual reality environments on mobile devices in 2011. As part of that, they also evaluated interactions such as navigation

and selection of objects. The main difference to applications for scientific visualization, or more specifically flow visualization, is, that in a game the user usually wants to explore a virtual world, not an object. So the task is to navigate through a scene and not to examine an object from different views and angles. Therefore results on game-related applications or virtual reality can not simply be transferred to scientific visualization. Thus further examinations have to be done.

The LiverExplorer [MEVIS] for mobile devices developed by the Fraunhofer MEVIS institute demonstrates that tablet PCs can be of great use in the medical field. Moreover it is a good example for the use of mobile devices in augmented reality applications. The app supports surgeons by providing interactive access to patient data during liver surgery. It offers augmented reality features, such as the overlay of planning data over the actual liver on the operation table. Moreover the app enables the surgeon to adapt to new intra-operative situations. One can for example measure the length of vessel branch sections with touch gestures or compute the volume drained or supported by any branch. The app was first tested in August 2013.

Other research shows that tablet PCs could also be useful for applications concerned with flow fields. Mouton et al. for example studied current systems and future trends in collaborative visualization in 2011 [MSG11]. In their review they included a transatlantic collaborative visualization with [ParaViewWeb], for which they utilized an iPad amongst others.

As mentioned before, one research focus is utilization of mobile devices in augmented reality applications. One example, that is concerned with flow fields, was presented by Eißele et al. in 2008 [EKE08]. They presented a visualization system that used a tablet PC as AR window and rendered visualizations of a flow simulation directly onto a flow channel in the real world. The rendering was remote.

In general the existing systems for flow visualization on tablet PCs are usually based on rendering clusters that can be accessed through a browser, such as [ParaViewWeb], or use remote rendering. That restricts the mobility aspects of mobile devices significantly. Therefore this project explores the possibilities of a standalone system and a client-server approach.

1.2 Structure of the Thesis

In Chapter 2 the fundamentals of flow visualization are introduced. That includes a description of flow datasets as well as an overview over common visualization techniques. Within that the aspects of flow visualization are emphasized.

Next the implementation process is described in Chapter 3. First the requirements for this project are stated. Then the utilized visualization libraries are introduced. After a description of the general design ideas, the implementation of the two applications, that were created for this project, are explained in more detail. The chapter concludes with an introduction to the user interface.

Then the next two chapters are concerned with the testing and evaluation of the applications. Chapter 4 treats the performance tests that were conducted. After shortly introducing the utilized datasets, the three experiments are explained and the results are given. In Chapter 5 the usability evaluation is described. First the notion of usability is introduced, followed by an overview over evaluation techniques. Then the evaluation setting, chosen for this project, is explained, including the utilized questionnaire. At last the results are given.

This thesis concludes with a short summary and a discussion of this work in Chapter 6. Additionally a proposal for future work is given.

Chapter 2

Fundamentals

In this chapter an overview over the fundamentals of flow visualization is given. First the typical structure of flow datasets is introduced in Section 2.1. Then some common visualization techniques for grids and scalar fields are described in Section 2.2. Finally in Section 2.3 flow visualization techniques are presented.

2.1 Flow Field Datasets

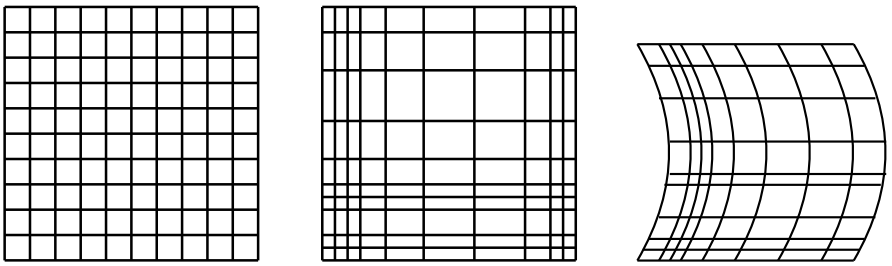
The aim of scientific flow visualization is to display scalar, vector and/or tensor fields such that the user gains more insight on their structure. The data is usually generated by a numerical simulation, but it can also result from experiments. A dataset can consist of several different attributed data fields. These data attributes can be time-variant.

In order to discretize the data fields, different types of grids are used. In these grids, the data attributes, i.e. the scalar or vector values, are associated either to the intersection points or to the cells, which are topological objects. In Figure 2.1 the differences between scalar point and cell data is shown. Scalar values are usually indicated by colouring. In Figure 2.1(a) the scalar values of the points are interpolated over the rectangles. Whereas the association of the scalar values to the rectangle cells, as shown in Figure 2.1(b), result in a constant color. Usually the data attributes are associated with points. The colour mapping is described in more detail in Section 2.2.2.

(a) Point Data (b) Cell Data

FIGURE 2.1: The difference between associating scalar values to points or to cells.

As mentioned before, there are different types of grids, depending on the type of data and the way the data was accumulated. In Figure 2.2 the characteristics of structured grids are depicted with the example of 2D data.



(a) Uniform Rectilinear (b) Rectilinear (c) Curvilinear

FIGURE 2.2: The characteristics of the different types of structured of grids, exemplified with 2D data.

There are three types of structured grids: uniform rectilinear, non-uniform rectilinear and curvilinear. In a structured grid, the cells can be indexed with a unique integer tuple. In this way it is easy to determine neighbouring cells.

Structured grids always consist of one cell type. In 2D the common cell types are rectangular and sometimes triangular, while in 3D hexahedrons and tetrahedrons are used.

In Figure 2.2(a) a uniform rectilinear grid, also called Cartesian grid or in 2D image Data, is shown. It consists of par-axial cells with the same edge length. It is the easiest to store and process. But at the same time it is very limited in terms of adjusting to the characteristics of a specific dataset. All regions of the grid have the same resolution.

The non-uniform rectilinear grid, depicted in Figure 2.2(b), is slightly more flexible. It consists also of par-axial cells, but sizes of these cells may differ.

In Figure 2.2(c) a curvilinear grid is shown. It is also structured, i.e. provides a unique integer tuple mapping to the cells, but the cells are not necessarily par-axial. The lines of the grid can be defined by parametric curves. This allows for a better adjustment to different datasets.

The higher the resolution of a grid, the more exact the data is represented. For flow field data, the information in some regions of the grid, for example close to the surface of an object, can be more important than others. So it can be useful to adjust the resolution of the grid to the structure of the dataset. This can be achieved by using unstructured grids. These grids have no regular cell structure and they can contain polyhedron cells.

Figure 2.3 shows an unstructured grid of a shuttle dataset. It can be seen that the cells of the grid have different sizes. Close to the surface of the shuttle, the cells are smaller, i.e. the resolution of the grid is higher. Moreover it can be observed that some cells close to the surface are rectangular, while most of the other cells are triangular.

Although the adaptive resolution of the grid reduces the amount of data, the processing of unstructured grids is more complex compared to structured grids. The vertices of the grids have to be stored explicitly. Moreover the cell formation provides no neighbour structure.

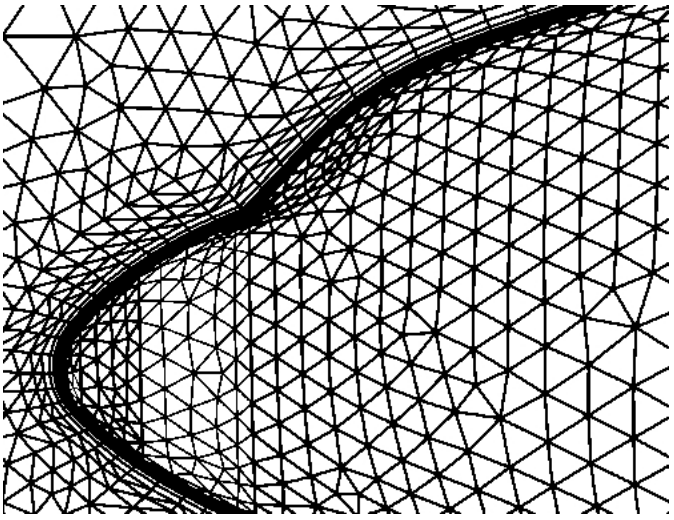


FIGURE 2.3: The unstructured grid of a flow simulation of a shuttle, provided by [NASA].

2.2 Visualization Techniques

Flow field datasets usually contain a lot of information and in most cases it is not possible to get an understanding of all aspects of the dataset in just one visualization. So in order to examine different aspects of the dataset, different visualization techniques are utilized. In the following common techniques for flow field data are introduced.

2.2.1 Grid Surface

The most basic visual representation of a dataset is its surface. Depending on the type of grid, the extraction of the surface faces is accomplished with different methods. For structured grids, the extraction of the surface is fairly easy, since the surface vertices are determined by their indices. Moreover the formation of the surface vertices, i.e. which vertices form a face, is also given by the uniform indexing. So the surface of structured grids can be constructed from the list of indexed vertices.

That does not hold for unstructured grids. But another property can be used: A face belongs to the surface if and only if it is part of exactly one cell of the grid. So in order to extract the surface of an unstructured grid, all faces of the grid have to be examined on whether they belong to one or to two cells.

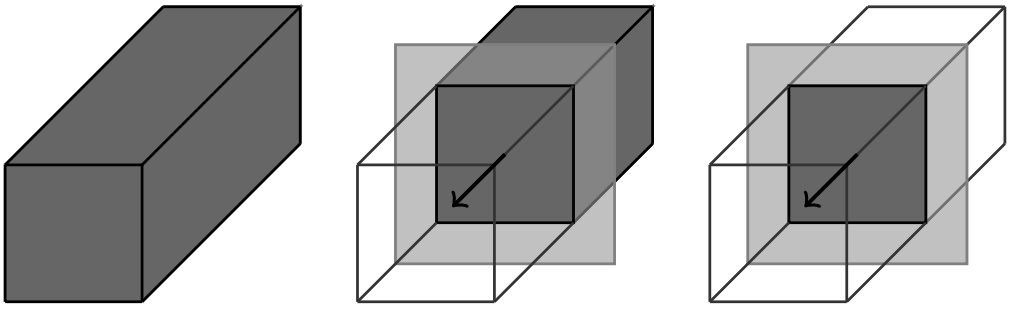
2.2.2 Colour Mapping

A common technique to visualize scalar data is the colouring of the rendered surfaces. First a transfer function needs to be defined. This function maps colours to scalar values. For the visualization it is discretized to a look-up table, where the scalar values serve as indices and the entries are colour values. Scalar values, that exceed the boundaries of the look-up table, are clamped.

The design of the transfer function is crucial for the comprehensibility of the visualization. For example scalar data representing temperatures are usually displayed such that low values are blue and high values are red. But when the scalar data refers to landscape heights, color maps normally range from blue for the sea level, i.e. the smallest scalar values, over green for fields, brown for mountains up to white for the highest scalar values, the mountain tops. In medical images on the other hand, the luminance color map, ranging from black over grey to white, has come to be accepted.

2.2.3 Cross Section

The extraction of cross sections is a common technique to explore 3-dimensional datasets. It allows for the user to examine the inside of a volume.



(a) A Dataset (b) Clipping (c) Cutting

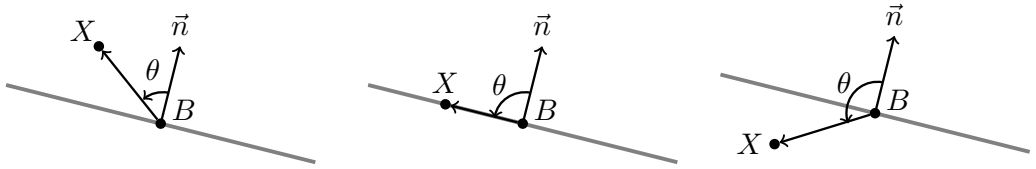
FIGURE 2.4: The two cross section visualizations, clipping and cutting. The transparent grey plane is the cross section and the arrow represents its normal vector.

Usually there are two methods to visualize a cross section: clipping and cutting. In Figure 2.4 these two methods are shown. While Figure 2.4(a) depicts some dataset, Figure 2.4(b) and Figure 2.4(c) display a cross section plane and the corresponding clipped, respectively cut, dataset.

With clipping the dataset is divided into two parts. The first one contains the data in front of the plane, defining the cross section, and the second part contains the rest, i.e. the data behind and in the plane. As a result only the second part is displayed, see Figure 2.4(b). Cutting on the other hand results in only the data in the cross section plane being rendered, see Figure 2.4(c).

The algorithms for clipping and cutting are similar. For all cells of the dataset it is checked whether the cell is intersected by the cross section plane, i.e. if there is at least one vertex of the cell on each side of the plane. In the clipping algorithm it is additionally determined which cells lie entirely behind the plane. For those cells which are intersected by the plane, the intersection with the plane is computed.

It is easily computed whether a vertex lies in front of, in or behind the cross section plane. Figure 2.5 depicts the three cases. It can be observed that these cases can be distinguished by the angle θ. That is by the angle between the plane's normal $\vec{n}$ and a vector $\overrightarrow{BX}$ from some point B in the plane to X, the point in question.



(a) In Front of the Plane (b) In the Plane (c) Behind the Plane

FIGURE 2.5: A point X is either in front of, in or behind a plane. These three different cases can be distinguished by the angle θ, that lies between the plane's normal $\vec{n}$ and the vector $\overrightarrow{BX}$, from some point B on the plane to the point X.

A point X lies in the plane for $\theta = \frac{\pi}{2}$ and for $\theta = \frac{3\pi}{2}$. Moreover it lies in front of the plane for $\theta \in [0, \frac{\pi}{2}[$ and $\theta \in]\frac{3\pi}{2}, 2\pi]$. For $\theta \in]\frac{\pi}{2}, \frac{3\pi}{2}[$ the point lies behind the plane.

With the dot product of two vectors given by $\vec{v} \cdot \vec{w} = \|\vec{v}\|\|\vec{w}\| \cos(\theta)$, it follows that:

- X lies in front of the plane if $\overrightarrow{BX} \cdot \vec{n} > 0$
- X lies on the plane if $\overrightarrow{BX} \cdot \vec{n} = 0$
- X lies behind the plane if $\overrightarrow{BX} \cdot \vec{n} < 0$

As a consequence the runtime of both cutting and clipping depends on the overall amount of cells and also on the number of cells that intersect with the cross section plane.

2.2.4 Iso-Surfaces

To examine scalar data, the visualization of iso-surfaces is a widely-used technique. An iso-surface is similar to a contour line. It is a surface that represents the set of points with the same constant scalar value. In Figure 2.6 an example of an iso-surface of the carotid dataset is given.

For the computation of an iso-surface the marching cubes algorithm is used. The algorithm examines the scalar values of the vertices of each cell in order to detect whether the cell is intersecting the iso-surface or not. That is if at least one value is equal, or at least one value is greater and one is smaller than the iso-value. By case distinction depending on the geometry of the cells, the resulting iso-surface can be computed. If necessary the intersection points are interpolated on the edges and connected to a surface. The time complexity of the algorithm is $O(n+k)$, where n is the number of vertices and k is the number of cells that intersect the iso-surface. For more details see Preim and Botha [PB13].

2.2.5 Volume Rendering

Volume rendering is used to create 2-dimensional graphic representations of scalar data defined on 3-dimensional grids. The basic idea is to make some boundaries of an object

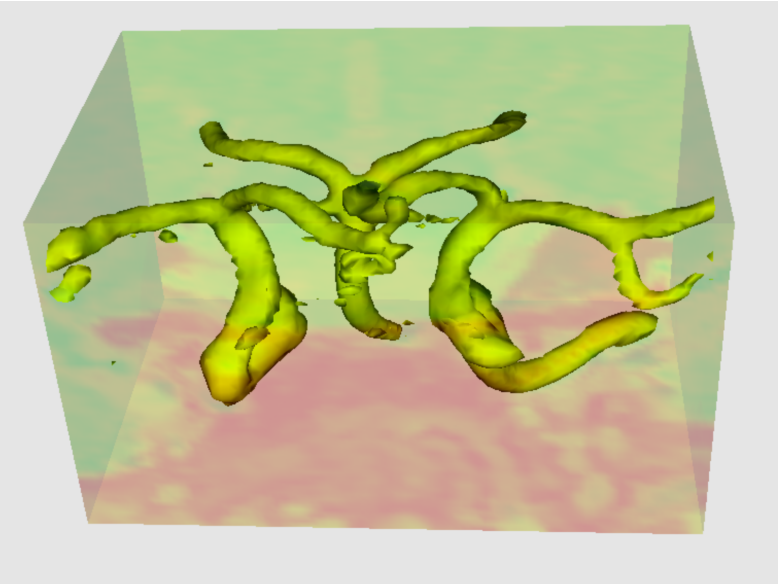


FIGURE 2.6: An iso-surface of the carotid dataset.

transparent, such that on can see inside and ultimately get a better understanding of the dataset.

There are two fundamental types of volume rendering: direct volume rendering and indirect volume rendering, also called surface-fitting rendering. Indirect volume rendering methods create surfaces, that are generally opaque. It includes for example the marching cube algorithm, i.e. iso-surface extraction.

With direct volume rendering on the other hand, the data can be considered as semi-transparent material and the user decides which parts of the object should be transparent or opaque. The voxels, i.e. cells, are mapped directly on pixels by integrating physical characteristics. Each voxel is projected in visibility order onto the image plane. In this way the pixel's final color and opacity is composed incrementally. As a consequence these methods are usually computational intensive and therefore not interactive. A common technique is ray casting.

For more information on volume rendering see Preim and Botha [PB13].

2.3 Vector Field Visualization

Due to the complexity of flow data and the variety of applications, there are many different techniques for flow visualization. There are 2D and 3D solutions as well as there are different methods for steady and for time-dependent flow fields.

In 2004 Laramee et al. gave a state of the art report on flow visualization [LHDVPW04]. In this paper the following distinction of the different techniques was made:

- *Direct Flow Visualization*: The direct visualization of raw flow data.

- *Dense, Texture-based Flow Visualization*: In order to generate a dense flow representation, similar to the direct flow visualization, a texture is computed from the flow data.
- *Geometric Flow Visualization*: Integration-based techniques are used to create geometric objects, such as lines, to represent flow properties.
- *Feature-based Flow Visualization*: First specific features of the flow data are extracted, such as important phenomena or topological information of the flow. Then this derived data is visualized.

Figure 2.7 depicts a schematic overview over the different flow visualization techniques.

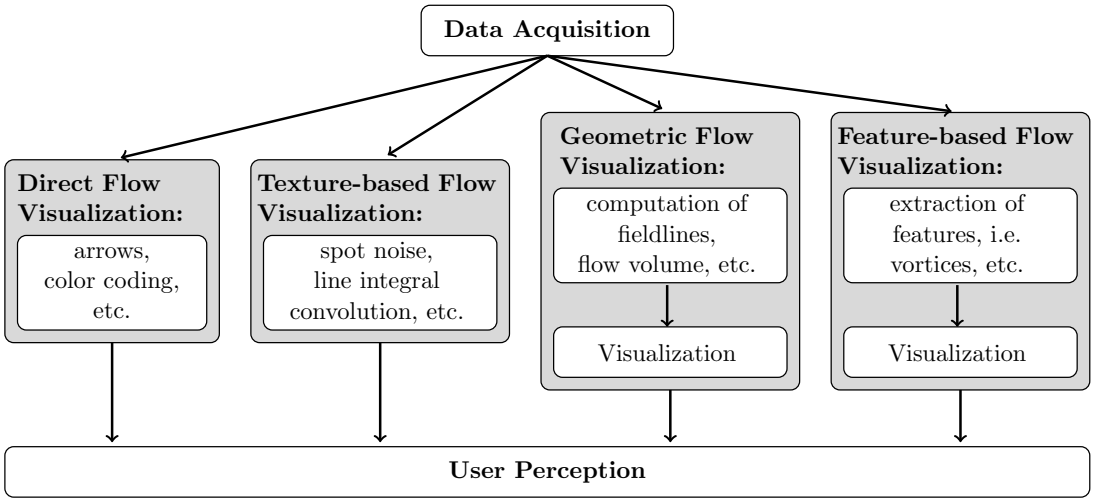


FIGURE 2.7: The different flow visualization techniques.

2.3.1 Direct Flow Visualization

This category of techniques makes direct use of the flow data. Unlike techniques from other categories, in direct flow visualization no preprocessing of the data is performed. That results in fast visualizations that allow for immediate examination of the data. Especially in 2D the resulting images can be very intuitive.

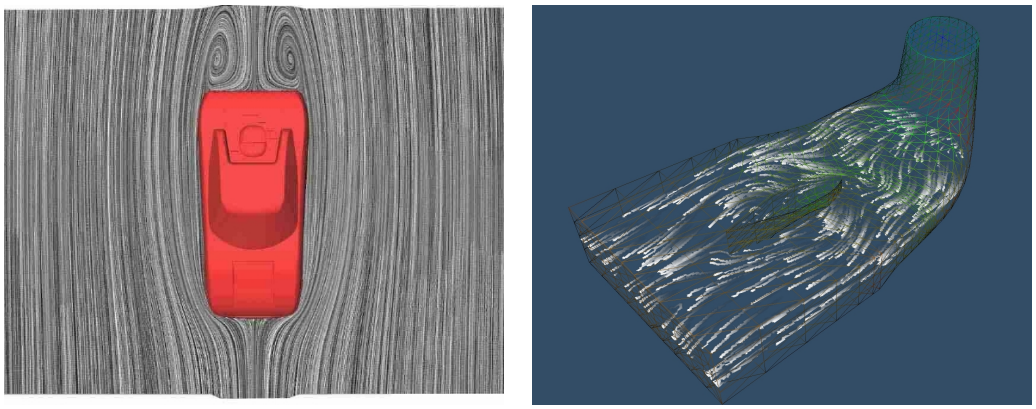
Common techniques are the drawing of arrows on the rendered surfaces, or color coding of the velocity of the flow.

2.3.2 Dense, Texture-based Flow Visualization

Texture-based flow visualization techniques apply the directional structure of a flow field on random textures. They are mainly used for visualizing flow in two dimensions or on surfaces.

A common techniques is called Line-Integral-Convolution (LIC). It was first proposed by Cabral and Leedom in 1993 [CL93] and has been picked up and developed further

by many others since then. The idea is to start with a white noise texture. Then for every pixel of the texture, the forward and backward streamline of a fixed arc length is computed. Finally the grey levels of all pixels that lie on this streamline are convoluted with a suitable convolution kernel, in order to get the grey value for the current pixel. As a result the grey values along one streamline strongly correlate, while the values show almost no correlation in other directions. In the resulting image the streamlines are set apart and become visible. Moreover this technique gives an overview over the entire flow on the 2D texture.



(a) Car Dataset (b) Turbine Dataset

FIGURE 2.8: Two different Line-Integral-Convolution textures, on the left a basic LIC texture and on the right an oriented LIC, also called OLIC, texture, from Benölken [B05].

For more details on dense, texture-based flow visualization, see Laramee et al. [LHDVPW04].

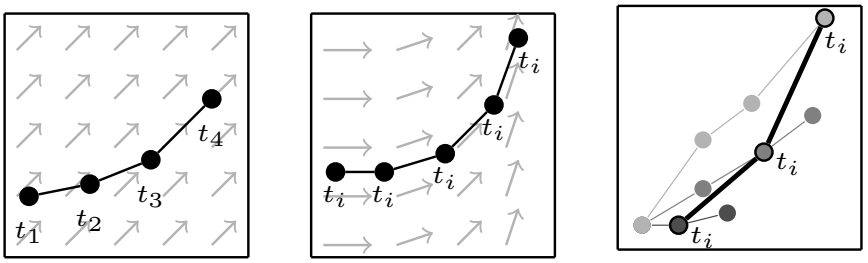
2.3.3 Geometric Flow Visualization

The first step in geometric flow visualization is the extraction of some geometry of the flow data. These geometric objects, that are directly related to the data, are usually based on integration. Examples of extracted geometry are field lines, stream surfaces, time surfaces, or flow volumes.

In a vector field, different kinds of field lines can be determined. These lines highlight different aspects of the vector field and help to gain insight on the characteristics of the flow field. In Figure 2.9 three types of field lines are shown.

Pathline A pathline is the trajectory a fluid particle follows, if it is set in the vector field at a specific place for a specific time. Figure 2.9(a) depicts a pathline and the corresponding vector field at time t_4. The first parts of the line were shaped by the vector field in earlier time steps.

Streamlines A streamline is connected to one point in time. For the vector field of this point in time, the streamline is tangent to the velocity vectors of the flow. It can be thought of as the pathline of a particle for a steady flow field. In Figure 2.9(b)



(a) Pathline (b) Streamline (c) Streakline

FIGURE 2.9: The characteristics of the different types of field lines.

a streamline and the corresponding vector field at time t_i are depicted. It can be observed that the streamline follows the vector field of this instant in time.

Streakline A streakline is the locus of particles that have earlier passed through a prescribed point. Dye injected into a flow field at a fixed point extends along the streakline. Figure 2.9(c) shows a streakline and three grey pathlines. Each of the pathlines passed the same point at a different instant of time. The streakline corresponds to the time t_i.

If the flow field is steady, i.e. it does not change over time, pathlines and streamlines coincide.

For flow field visualization, the computation of streamlines is a common technique. The vector field is interpreted as a velocity field, which serves as a differential equation. With a given starting point, also called seed-point, the generation of a streamline is equal to solving the initial value problem with a steady flow field as differential equation.

The initial value problem can be solved using numerical integration algorithms such as Runge-Kutta. For a detailed description see [Telea07].

2.3.4 Feature-based Flow Visualization

In feature-based flow visualization techniques the visualization is not based on the entire flow data, but on some extracted features. In a first step these features, such as important phenomena or topological information of the flow, are determined. Next these features are visualized, which may require further geometry extraction, depending on the specific technique. This approach allows for a compact and efficient way to visualize large and/or time-dependent datasets.

Common techniques include the extraction of vortices, i.e. turbulences, and shock waves, which are characterized by discontinuities in physical flow quantities. Both the definition on what interesting features are, as well as the way these features are extracted and visualized depend on the dataset, the application and the research area. For more details see Post et al. [PVHLD03].

Chapter 3

Implementation

In this chapter the design process and the final applications, that were implemented for this project, are described. First the main requirements are deducted from the task description in Section 3.1. Then the utilized visualization libraries are introduced in Section 3.2. In Section 3.3 the three main design ideas are explained with regard to the implementation, which gives a first overview over the structure of the applications. It follows a more detailed description of the standalone app in Section 3.4 and of the client-server app in Section 3.5. The chapter is concluded with an introduction to the user interface in Section 3.6.

3.1 Requirements

The objective of this project is to create a system for the interactive exploration of flow fields on a tablet PC. Furthermore this system shall be used to examine the possibilities and the limits of scientific visualization on tablet PCs with regard to flow fields.

From this task description two sets of requirements arise.

3.1.1 Visualization of Flow Fields

Firstly, the application should be able to process flow field datasets. Such a dataset usually includes a 3-dimensional grid with optional scalar, vector or tensor values. In order to give an overview over the suitability of a tablet for flow visualization, it suffices to restrict the datasets to scalar and vector fields. The use of advanced techniques for time-variant datasets is not addressed.

In order to explore a flow field dataset, different visual representations are used. That includes cut-planes, iso-surfaces and streamlines. It follows that the application is required to offer these common visualization techniques.

Additionally the rendering should be fluent, so that the application is interactive. The user needs to be able to rotate, translate and zoom the visualized content, in order to get

a good understanding of the dataset. So the application is required to provide real-time rendering, i.e. the rendering has to be fast enough for the user not to notice any delay. The user should experience dynamic movements and not separated images.

3.1.2 Examining the Potential of Tablet PCs

To examine the potential and the constraints of a tablet PC for flow field visualization, the application should be rendered on a tablet PC. Furthermore the use of additional hardware should not limit the mobility of the tablet PC. The mobility is the main advantage and difference of the tablet PC compared to desktop or laptop PCs. A tablet PC functions wireless and can easily be carried around without spatial limitations. So the application should be constructed in a way that this advantage can still be used. Otherwise there is not much difference to a desktop or laptop PC.

Additionally the user interaction possibilities of the tablet PC should be utilized. The biggest difference to traditional desktop or laptop PCs is the touch screen. But other options, such as the gyroscope, should also be explored.

3.1.3 Design Decisions

Due to the aforementioned requirements and external circumstances three general decisions were made for this project.

Firstly, it was decided to use the iPad 4 as basis of this project. At the time when this project started, in the beginning of 2013, only iOS- or Android-based tablet PCs were available. And since the University of Cologne has a master agreement with Apple and the iPad provides powerful hardware, it was the best choice.

Secondly, VTK was chosen as auxiliary library for the scientific visualization. It is a widely-used, open-source library that provides a wide range of visualization techniques for flow fields. Additionally there exists a viewer app for iOS based on VTK, which was used as starting point for this project. A detailed description is given in Section 3.2.

Thirdly, it was decided to create two versions of the same application, one standalone and one based on a client-server system. Since the processing of flow field datasets is computationally intensive, it is expected that the tablet PC reaches its limits with larger datasets. So in order to examine these limits and explore a possible solution, a client-server system will be created. This system should be wireless. Moreover it should be realized on a private network for safety reasons.

3.1.4 User Interaction Techniques

A requirement for this project is the design of user interaction methods that use the advantages of a tablet PC and enhance applications for flow visualization. The main differences in terms of use interaction between a desktop PC and a tablet PC are the

touch screen, the accelerometer and the gyroscope. So the interaction methods implemented for this project should use these possibilities.

The touch screen is used to navigate the scene. As described in Section 3.6, there are five different touch gestures to rotate, translate and zoom the scene.

Additionally an auxiliary plane widget is implemented. It is used to place cut-planes and seed-points. The widget is navigated with touch gestures.

Utilizing the Gyroscope

There were also attempts to utilize the gyroscope. The idea was to implement a rotation of the scene linked to the gyroscope, such that tilting the tablet PC into one direction, for example left, would result in the scene being rotated in the opposite direction, i.e. right. The desired effect would have been to create the illusion of navigation to the left in the virtual world. A similar approach is described by Hürst and Helder [HH11]. The rotation was implemented as an optional feature, that could be turned on and off with a button.

But it became clear early in the project, that this technique is not suitable. The biggest issue was the imprecision. It was very difficult to tilt the tablet PC accurately to achieve the desired rotation, even with different sensor sensitivities. Mainly because it was not easy to control the device such that it tilted exactly in one direction.

Moreover the range, in which the screen can be tilted with the user still being able to view the scene, is limited. The maximum tilt angle is about 30° in each direction from the starting orientation. So the maximum range is about 60° in each direction. So either one maps these 60° to 60° of rotation range, which seems intuitive, or to 360° in order to enable a full turn of the scene with one gesture. The first option works only if the tilting can be activated with a button. Then exploring the scene becomes very complex, with activating the rotation, performing the tilting, deactivating the rotation, tilting back to the starting point, activating the rotation, etc. . That does not only impede the exploration of the scene, but it is also very difficult to maintain a precise rotation. But mapping the 60° of tilting range to 360° of rotation also does not result in a satisfying interaction method. The rotation gets so sensitive, that the movements are even harder to control.

So after testing and tweaking different options, it became clear that the gyroscope-based rotation has no advantages to touch-based rotation. It was bulky and inaccurate. As a consequence this interaction method was withdrawn from the applications.

3.2 Visualization Libraries

The visualization for this project is based on three libraries, VTK, VES and Kiwi. These libraries are built up on each other, which is depicted in Figure 3.1. Whereas VTK is

used for scientific visualization, VES extends VTK for embedded systems and Kiwi facilitates the use of VTK and VES in an Android or iOS application.

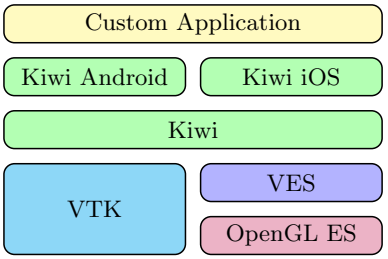


FIGURE 3.1: The relation of the visualization libraries VTK, VES and Kiwi.

3.2.1 VTK

VTK [VTK] is a software for 3D computer graphics, image processing and visualization that was initially created in 1993 as part of the book "The Visualization Toolkit: An Object-Oriented Approach to 3D Graphics" published by Prentice-Hall. Since 1998 it is developed by Kitware, Inc. . It is free and open-source, licensed under the BSD license. It consists of a C++ library and several interpreted interface layers including Python, Tcl/Tk and Java. Moreover it is cross-platform and runs on Linux, Windows, Mac and Unix platforms. The newest version 6.0 was released on 27. June 2013.

VTK offers several visualization algorithms including vector, tensor, texture and volumetric methods. Furthermore the tool kit provides advanced modelling techniques such as implicit modelling, polygon reduction, mesh smoothing, cutting, contouring and Delaunay triangulation. Additionally it contains an information visualization framework and supports parallel processing.

The framework also includes support for user interaction, for example with a suite of 3D interaction widgets. Moreover it integrates with various databases on GUI tool kits such as Qt or Tk.

The fundamental structure of VTK is the data flow pipeline, transforming a source of information into a rendered image. This pipeline is depicted in Figure 3.2. The first part of the pipeline, marked blue and green in the figure, is the visualization pipeline. Here the data is read and filtered and then the essential parts for the visualization are extracted. The second part of the pipeline, marked green and yellow in the figure, handles the graphical model, i.e. the transformation from a set of polygons in 3D to pixels on the screen. The green element, the mapper, belongs to both parts of the pipeline.

FIGURE 3.2: The visualization pipeline of the Visualization Toolkit VTK. The blue colouring specifies the visualization pipeline, the graphics model is indicated in yellow and green part belongs to both of them.

3.2.2 VES

VTK is used to build desktop applications and some modules, most importantly the rendering module, are based on OpenGL. VES [VES] provides an OpenGL ES 2.0 based rendering library that integrates with the rest of VTK. The framework is also free and open-source, released under the Apache 2.0 license. The VES library dependencies are VTK and Eigen [Eigen], a linear algebra library which is licensed with the MPL 2.0 license.

VES is also developed by Kitware, Inc. and the latest version is 1.0.0 that was released 24. January 2012.

VES enables the use of a lot of VTK modules for mobile applications. However there are still VTK modules that are based on OpenGL, for which VES does not provide an OpenGL ES solution. For example the module *vtkRenderingAnnotationModule*, which is needed to use color bars, is not yet available.

In the VTK pipeline from Figure 3.2, VES replaces the graphic model part, i.e. the mappers, actors and the renderer. Moreover it provides a scene graph structure additionally to the pipeline. This scene graph is used to organize the different objects in the scene both spatially and logically. While the VTK pipeline is still used to transform a source of information into data that can be rendered, the rendering process is handled by the scene graph. Therefore the actors also serve as nodes in the scene graph.

Different from VTK, VES only renders polygon sets of type *vtkPolyData* and no grids or point sets. Therefore other datasets have to be converted, which can be done with VTK.

In addition VES provides standard shaders such as Blinn-Phon, Gouraud and Toon, and supports textures.

3.2.3 Kiwi

The Kiwi framework [VES] consists of C++ classes that facilitate the use of VTK and VES in an Android or iOS application. It bundles together the required rendering components, I/O routines and scene objects into a set of interfaces. Additionally Kiwi provides 3D widgets designed for touch screens that allow for data manipulation and interaction with the 3D scene by the user.

KiwiViewer

The KiwiViewer [Kiwi] is an open-source application created with the VES and Kiwi libraries that is published under the Apache 2.0 license by Kitware, Inc. . With this application geometric datasets can be explored on multi-touch mobile devices. The first version 0.0.2 was released on 19 January 2012. The latest release was version 2.0 on 6 March 2013.

The early versions support the rendering of geometric 2D or 3D datasets with scalar attributes as colour. The model can be navigated, i.e. rotated or zoomed, with touch gestures. In the latest app various ways for sharing data were added. Moreover the visualization engine was improved and more file formats are supported. The viewer now allows for textured meshes, time-series data and animations. Furthermore there is the possibility to connect to a ParaView desktop application for remote rendering, although this technology is not yet fully developed.

In contrast to the applications developed for this project, the KiwiViewer is a solely a viewer. It reads datasets or animations from files and displays the content. There is no interactive visualization, with for example cut-planes or streamlines, applicable for all datasets. Although there is one interactive example scene utilizing cut-planes, the SPL-PNL Brain Atlas, that functionality is customized for this one demo dataset only.

3.3 General Design

There are three basic design principles underlying the *TabletVis* app. The delegation pattern is used as basis for the main run loop of the app. The interaction of user input, layout and logical components is organized following the Model-View-Controller pattern. Furthermore the VTK related logic is based on a pipeline-design.

3.3.1 Delegation

The delegation pattern describes a relationship between two objects, the delegator and the delegate, see [Gamma94]. In iOS-based apps, the delegator is always the UIApplication object, whereas the delegate is an app-specific custom object.

The delegator, i.e. the UIApplication object, keeps a reference to the delegate. Whenever necessary the delegator notifies its delegate of events it is about to handle or has just handled. Then the delegate may react to this message by updating its state, its appearance or other objects in the application. In this way the control over the app's behaviour is centralized in one object, the application delegate.

The use of this pattern also influenced the design of the main run-loop.

The Main Run-Loop

When the application is launched, the UIMainApplication is called. Amongst other things, this function creates the UIApplication singleton for the application. This object then initiates the main run loop that is depicted in Figure 3.3.

The main run loop is responsible for processing all user-related events in the application. It starts with some kind of user interaction, for example a touch on the screen. When this touch is detected, the operating system translates it into the corresponding system events.

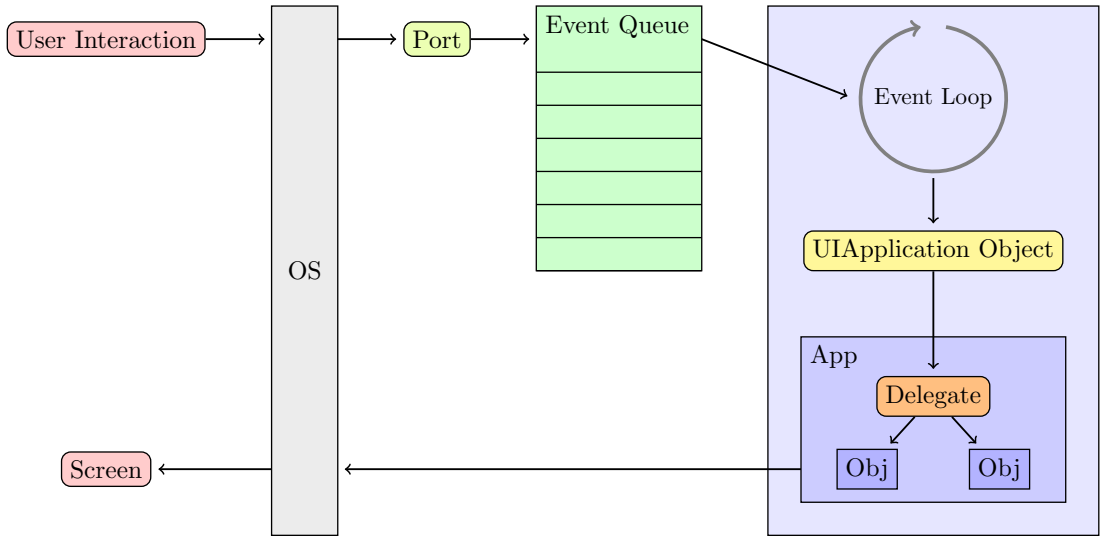


FIGURE 3.3: A schematic view of the main run loop in an iOS application.

Via a special port that was set up by UIKit, these events get transmitted to the event queue. From here the events get dispatched one-by-one to the event loop of the application. From this loop the events finally reach the UIApplication object.

The UIApplication object is the delegator object in the application. Depending on the type of event and the concrete implementation, the UIApplication object performs the corresponding event handling with or without notifying the application delegate.

If the delegate gets notified this may provoke additional actions from other core objects. Touch events for example usually get dispatched to the main window object, which then notify the respective view for further actions.

3.3.2 Model-View-Controller

The Model-View-Controller pattern is used for implementing user interfaces, see [Gamma94]. It separates a program into three different interconnected parts. The exact responsibilities and interactions between these parts may differ slightly for different implementations.

An overview over the *TabletVis* standalone app arranged in the Model-View-Controller grouping is given in Figure 3.4. The yellow marked objects are iOS system objects. The objects that are part of both the standalone as well as the client-server app are marked green. The blue objects are also part of both versions, but are fairly modified. These modifications are described in Section 3.4 and Section 3.5.

In the *TabletVis* standalone app, the model contains the app-specific logic, i.e. the scientific visualization functionalities, and the data. The view handles the visual output and the user interaction. The controller acts as the link between the model and the view. It processes the user input, updates the model if necessary and passes changes concerning the visual output to the view.

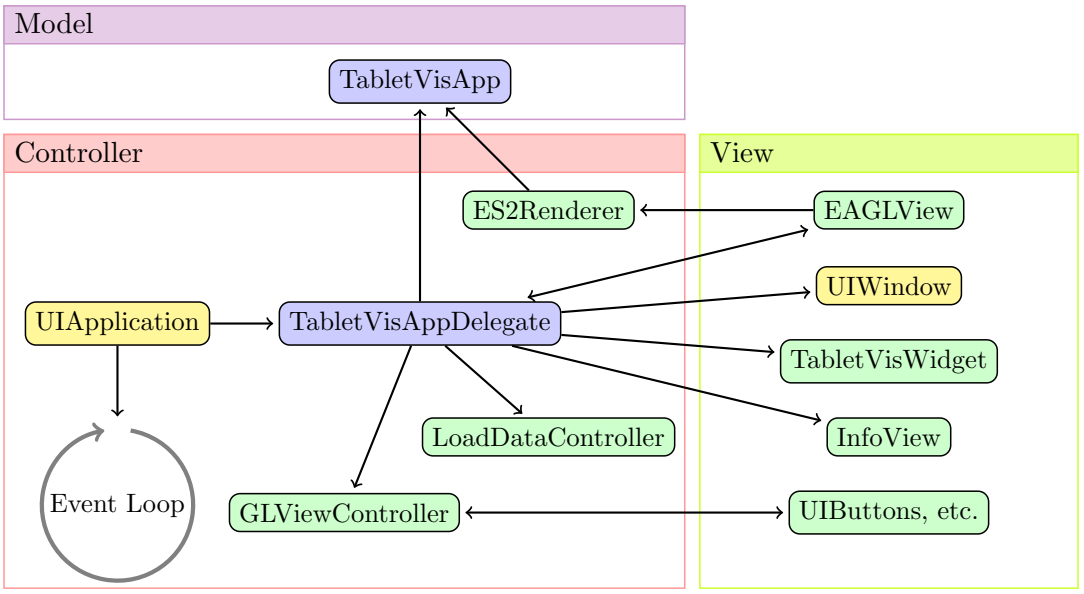


FIGURE 3.4: The core objects of the *TabletVis* standalone application arranged in the Model-View-Controller grouping.

As described in Section 3.3.1, the delegator, the UIApplication object, is notified about events such as a touch interaction by the event loop. It then passes the relevant events to its delegate. In the *TabletVis* app, the delegate is the *TabletVisAppDelegate*. In Figure 3.4 it can be observed that the delegate is the center of all other parts of the application.

TabletVisApp

The *TabletVisApp* object has different properties in the two versions of the app. In any case it provides access to the scenegraph. The scenegraph is hidden in the *vesRenderer*. But the *TabletVisApp* provides a limited interface, which includes the creation and deletion of nodes and the positioning in the scene.

In the standalone version the *TabletVisApp* also holds the VTK-related logic and the data. A description of the VTK-based parts of the app is given in Section 3.3.3. The detailed specifications for the different app versions are given in Section 3.4 and Section 3.5.

TabletVisAppDelegate

The *TabletVisAppDelegate* is the central controller and all user interaction events are handled here. That includes the behaviour when a certain button was tapped or a touch gesture performed. Additionally the delegate is the only part of the app that controls the model, i.e. the *TabletVisApp* object. The detailed specifications for the different app versions are given in Section 3.4 and Section 3.5.

GLViewController

The *GLViewController* represents an interface to the app's main window layout. In this class all sub-views of the main view are declared. So although the *TabletVisAppDelegate* controls for example the behaviour triggered by a button, this view-controller is the only object with access to the location and the appearance of the buttons.

The *GLViewController* serves as the root view-controller of the *UIWindow* of the delegate. That means that whenever the screen of the tablet is touched, the *UIApplication* object notifies the delegate, which refers the event to the window. The window then informs its root view-controller, in order to find out if a sub-view, i.e. a button, was tapped.

Moreover additional characteristics of the main view are controlled here, for example whether the view rotates correspondingly when the device is rotated or if it does not.

ES2Renderer

The *ES2Renderer* controls the rendering of the model-related content, i.e. the output of the VTK computations. It serves as an interface to the rendering functionality given by the *TabletVisApp*.

EAGLView

The *EAGLView* is the view which presents the visual output of the model. It wraps iOS classes such as *CAEAGLLayer* and provides a view into which an OpenGL ES scene can be rendered. The *EAGLView* uses the *ES2Renderer* in order to get the visual output of the *TabletVisApp*.

LoadDataController

The *LoadDataController* organizes a drop-down menu, which offers the available datasets. The *TabletVisAppDelegate* controls when this menu is displayed. When an item in the menu is tapped, the delegate is notified.

InfoView

The *InfoView* is a small view, which displays some basic information about the current dataset. That includes the number of triangles, vertices and the current frame-rate. The *TabletVisAppDelegate* controls when this view is displayed.

TabletVisWidget

The *TabletVisWidget* is an auxiliary interaction element. It consists of a plane with a normal. It is used to define cut-planes and to place seed-points for the generation of streamlines.

The *TabletVisWidget* class extends *vesKiwiPlaneWidget*. The widget can be in three different states: inactive, visible or seed-points. The inactive widget is not rendered and therefore receives no user input. The visible widget is used for cut-planes. It is rendered and can be manipulated with touch gestures. The seed-point state extends the visible state such that double tap gestures on the plane of the widget create seed-points.

The set of seed-points and its visual representation in the scenegraph is handled by the *TabletVisWidget* object, since the visibility of the seed-points is linked to the state of the widget.

3.3.3 Visualization Pipeline

As described in Section 3.2.1 the processing of datasets with VTK is realized with data flow pipelines. This system of pipelines is located differently in the two different app versions, which is explained in Section 3.4 and Section 3.5. In the standalone app, it is contained in the *TabletVisApp* as depicted in Figure 3.5. In the client-server app, the pipeline system is built the same, but it is contained in the server.

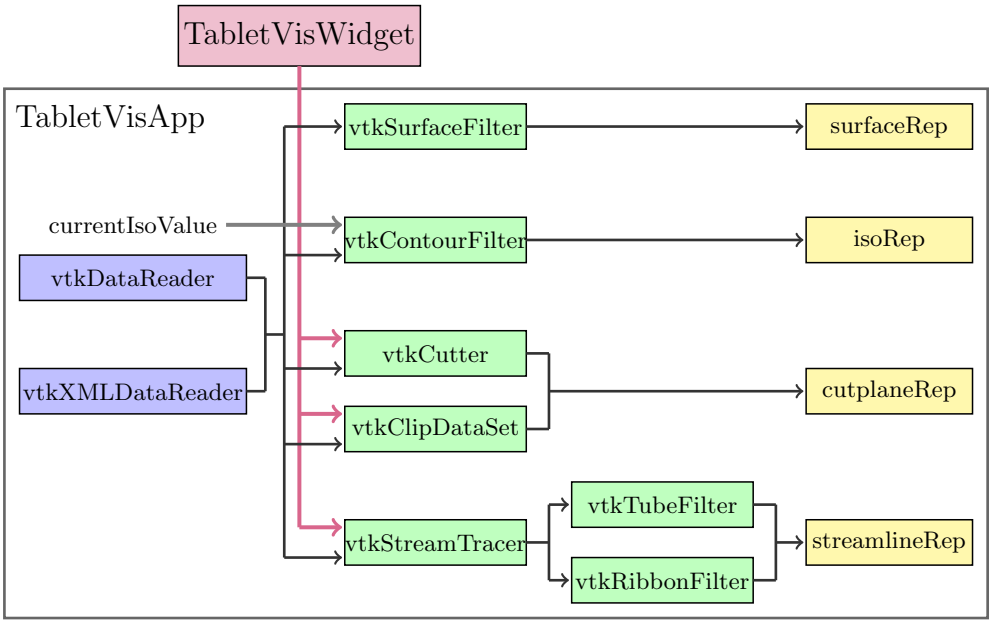


FIGURE 3.5: The pipeline built of VTK-modules.

In Figure 3.5 the blue elements represent the sources, the green elements are filters and the yellow elements are representations of polygon sets, i.e. nodes in the scenegraph. While the pipeline system is fully contained in the *TabletVisApp* class, some filters need input from the *TabletVisWidget* such as the coordinates of a cut-plane.

The distinction between the two data reader sources is that one reads the XML-based VTK-formats and the other one the other VTK-formats. Depending on the file-ending the corresponding reader is chosen and used as source.

There are three steps in the activation of a pipeline branch. First, when the corresponding perspective in the user interface is opened, the filters are initiated. Next the branch is executed. This second step is then repeated as often as the user requests. When the perspective is closed in the user interface, the filters get finalized and the corresponding visual representation is removed from the scenegraph.

The Surface Branch

After the dataset was read from the file, the *vtkSurfaceFilter* is used to extract the polygon set that represents the surface. Afterwards it is transferred to the surface representation in the scenegraph.

The Iso-Surface Branch

In order to extract an iso-surface, first the dataset is read. Next the *vtkContourFilter* extracts the polygon set representing the iso-surface for a given iso-value that was provided by the *TabletVisApp*. At last the resulting polygon set is transferred to the scenegraph representation.

The Cut-Plane Branch

For the cut-plane branch there exist two different filters. The *vtkCutter* extracts only a slice of the model, i.e. the filter produces a plane. The *vtkClipDataSet* filter clips a part of the model, such that the resulting polygon set represents the surface of one part of the model.

Both filters take the dataset and and the coordinates of the cut-plane as input. Depending on the user input either the slice or the clipping filter are used. Only one cut-plane filter result is then transferred to the scenegraph representation.

The Streamline Branch

The integration of the vector field, i.e. the generation of the streamlines, is executed in the *vtkStreamTracer* filter. It takes the dataset and a set of seed-points as input. The seed-points are provided by the *TabletVisWidget*.

The *vtkStreamTracer* produces poly-lines, sets of consecutive points. There are two different options to visualize these results, tubes and ribbons. In order to compute polygon sets that represent the computed streamlines, one of two additional filters are used. The *vtkTubeFilter* produces tube-shaped and the *vtkRibbonFilter* ribbon-shaped polygon sets. Only one set of streamline representations is passed to the scenegraph.

3.4 The Standalone Version

In Figure 3.6 the main objects relevant for the visualization in the standalone *TabletVis* application are shown.

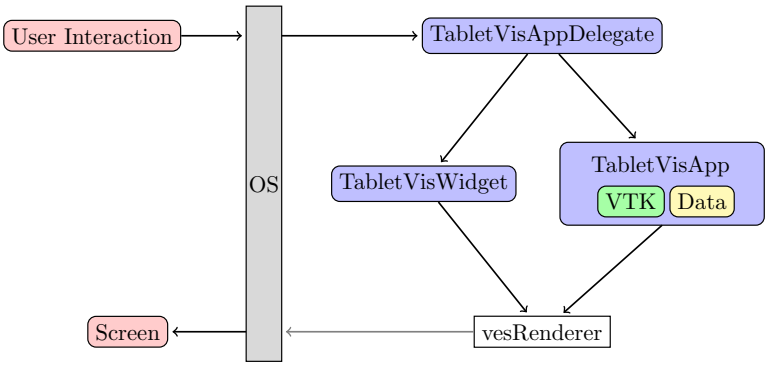


FIGURE 3.6: A schematic view of the standalone version of the *TabletVis* app.

TabletVisAppDelegate

The *TabletVisAppDelegate* object manages all app-specific behaviour. This is were all app-related objects are bundled and managed. The user input is passed from the *UIApplication* object to the delegate. Touch gestures get passed on to the *TabletVisApp* and the *TabletVisWidget* objects. Moreover the behaviour of buttons is defined in the delegate.

Whenever the user requests an action that requires the use of VTK functionality or a change in the scene, the delegate notifies the *TabletVisApp* and/or the *TabletVisWidget*. In Figure 3.7 it is shown how the standalone app handles the request for a clipping plane.

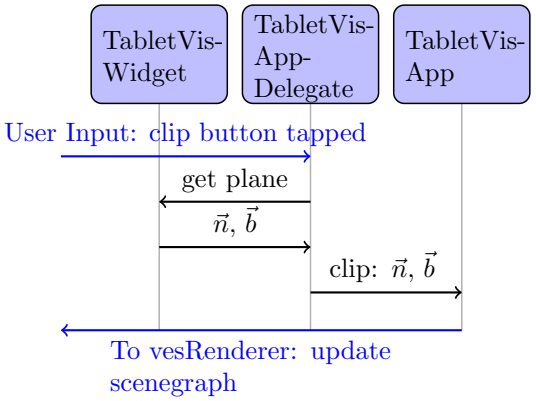


FIGURE 3.7: The standalone communication for the computation of a clipping plane.

The *TabletVisAppDelegate* gets notified of user input that require the clipping by a cut-plane. It then inquires the plane equation of the *TabletVisWidget*, which defines the cut-plane. Next the delegate orders the *TabletVisApp* to perform a clipping action with

the given plane equation. The *TabletVisApp* performs the clipping, and updates the scenegraph.

TabletVisApp

The VTK logic, i.e. the pipeline system presented in Section 3.3.3, is contained in the *TablteVisApp* class which extends *vesKiwiViewerApp*. Additionally the *TabletVisApp* class handles the rotation, translation and zoom of the scene. Furthermore the *TabletVisApp* stores the paths to the available dataset files.

3.5 The Server-Client System

The server-client version of the *TabletVisApp* is derived from the standalone version. It enables client-side rendering, where all computations are performed by the server. An overview over the relevant classes is shown in Figure 3.8.

The communication of client and server is realized using BSD sockets and the IPv6 protocol. Moreover [Bonjour], Apple's so called zero-configuration networking service, is used to establish the connection.

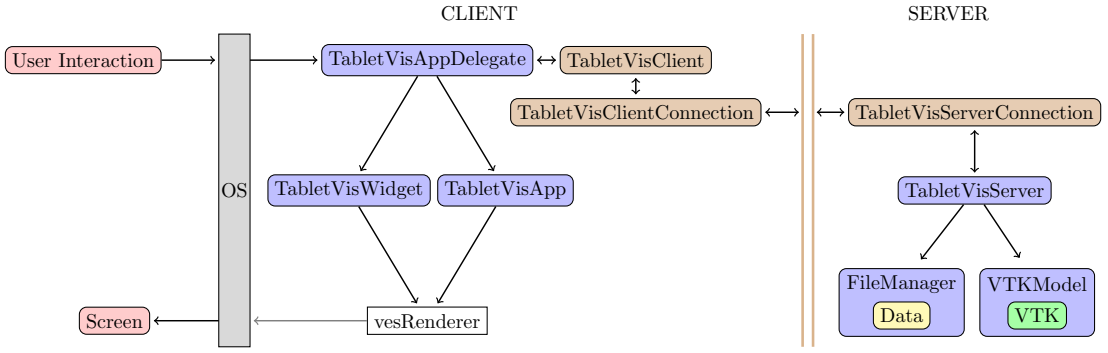


FIGURE 3.8: A schematic view of the client-server version of the *TabletVis* app.

To start the system, both the server and the client application are started, without a specific order. But it is important that both devices are connected to the same local network, so that the client can detect the server. After a few seconds, the client app will show all available servers and one has to be chosen to start a connection.

Additionally to the functionality of the standalone version, the client-server system provides also the possibility to switch the scalar data of a model. Datasets can contain several data fields and it is not uncommon that more than one scalar field is included, for example temperature and pressure values. This functionality can also be added to the standalone version, if it proves capable of handling large datasets.

3.5.1 Client-Side

After establishing a connection the client asks the server for the list of names of the available datasets, in order to build the dropdown menu. Then the app waits for user input.

TabletVisAppDelegate

Similar to the standalone app, the user input is handled and transferred by the *TabletVisAppDelegate*. Whenever a computation from the server is needed, the delegate provides the *TabletVisClient* with the necessary information, such as the coordinates of the plane widget or an iso-value, to request the computation from the server. The delegate is also responsible for handling the messages from the server that are translated by the *TabletVisClient*. The detailed communication process is described in Section 3.5.3.

TabletVisApp

In contrast to the standalone version of the application, the *TabletVisApp* in the client does not contain any VTK logic. But it still provides an interface to the scenegraph. Moreover it also still holds the list of available datasets that was sent by the server.

TabletVisClient

The *TabletVisClient* is used as an interface to the server for the *TabletVisAppDelegate*. It translates the requests of the delegate into a message, that can be read by the server. Additionally it also translates messages from the server into actions for the delegate. That may include decompressing the server's answer.

For the communication with the sever the *TabletVisClient* uses a *TabletVisClientConnection* object.

TabletVisClientConnection

The *TabletVisClientConnection* bundles the low level connection details on the client-side. That includes controlling the socket and its input- and output-streams. The *TabletVisClient* passes the message for the server to the *TabletVisClientConnection* which is then responsible for transferring it to the server. When the server answers, the *TabletVisClientConnection* gathers all incoming bytes until it reaches the coding for the end of the message. Only then does it transfer the complete message to the *TabletVisClient*.

3.5.2 Server-Side

TabletVisServerConnection

The *TabletVisServerConnection* is the counterpart to the *TabletVisClientConnection*. Since the server is designed such that it could be extended to handle several clients, the sockets are controlled by the *TabletVisServer*. The *TabletVisServerConnection* controls the input- and output-streams. Additionally it is responsible for the compression of the answers sent to the client.

Whenever the *TabletVisServerConnection* receives information from the client it passes the complete message to the *TabletVisServer*.

TabletVisServer

The *TabletVisServer* is the main controller on the server-side, which includes the handling of the sockets. Moreover it is responsible for performing the client's request with the use of the *VTKModel* and the *FileManager*. First it receives a message form the *TabletVisServerConnection*, which it translates into an action request. Then it executes this action and answers the result to the client.

VTKModel

The *VTKModel* contains the VTK functionality. It stores a synchronized version of the *TabletVisApp* from the client-side. That means, if the iso-surface perspective is opened on the client, the *VTKModel* has the necessary filters prepared. It therefore also needs to get notified is a perspective is closed.

FileManager

The *FileManager* handles the available files. When the server is started, the path to the data directory has to be passed. From this directory all files in a VTK format are detected and proposed to the client. In contrast to the standalone version of the app, the client-server system does not support the loading of files from Dropbox.

3.5.3 The Communication

The general process of communication between server and client starts with the client. And the server always answers, even if there is no data that needs to be transmitted. In this way the client knows that the server received its message.

In order to reduce the amount of transmitted data, the compression of messages from the server-side can be activated. That is explained in more detail at the end of this section.

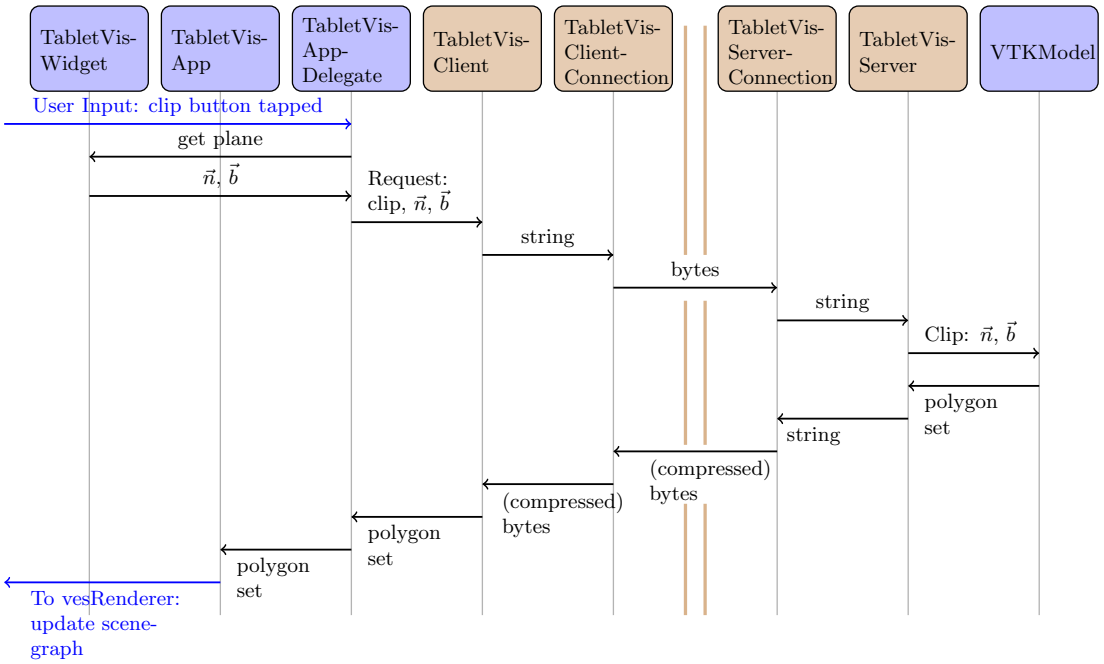


FIGURE 3.9: The client-server communication for the computation of a clipping plane.

In Figure 3.9 the communication between client and server is depicted using the example of a clipping request.

It starts with some input from the user, in this case the *clip*-button was tapped, which is passed to the *TabletVisAppDelegate*. Since the positioning of the *TabletVisWidget* is required for the clipping computation, the delegate demands it plane equation. Then it passes the request and the plane equation to the *TabletVisClient*.

The *TabletVisClient* translates the request into a code that can be read by the server. In general this code starts with a request number. There are 14 different types of requests and each can be identified by its request number. Then some additional information, such as the plane equation, might follow. Depending on this additional information, the code is formatted slightly different. But since the server knows which request is followed by which additional information, it knows how to interpret the message. In case of a clipping request, the message looks as follows:

$$2|n_1\ n_2\ n_3\ b_1\ b_2\ b_3|$$

Clipping has the request number 2, $\vec{n}$ represents the normal and $\vec{b}$ the origin of the cut-plane.

From the *TabletVisClient* this message gets transferred to the *TabletVisClientConnection* which transmits it to the *TabletVisServerConnection*. There the message is gathered and the complete set of bytes is passed to the *TabletVisServer*. This is where the message is read and translated into actions.

After the *TabletVisServer* demanded the *VTKModel* to perform the clipping with the sent plane equation, it receives the resulting set of polygons. With this the *TabletVisServer* assembles the answer for the client, which is coded similarly to the initial request. It starts with the request number of the handled action. Then some additional information may follow. In some cases there is no such information, for example when the client notified the server that a certain perspective in the user interface was closed. But in most cases the server transfers a set of polygons. The serialization of the set is done using VTK and by default in binary coding. It is written in the VTK legacy file format. In case of a clipping request, the answer in ASCII coding would look like the following:

2|# vtk DataFile Version x.0 name ASCII DATASET POLYDATA
POINTS n float x_1 y_1 z_1 ... x_n y_n z_n
POLYGONS m p f_1 v_a v_b v_c ... f_m v_i v_j v_k
POINT_DATA n SCALARS name float 1 LOOKUP_TABLE default s_1 ... s_n|

Since clipping has the request number 2, the message starts with that number. The first line represents the VTK header, which specifies the utilized VTK version, the type of the coding and of the dataset.

In the next line the coordinates of the n vertices of the polygon set are listed. It follows the specification of the m polygons. The integer p indicates how many integers are going to follow. For each polygon the number of vertices f_i is stated first. Then an ordered list of the indices of these vertices follows. The indices are related to the order in which the coordinates of the vertices were declared in the line before.

In the last line the colours of the vertices are given in form of a scalar set. With a lookup table each scalar value is assigned to a colour. The keyword POINT_DATA specifies that the scalars are associated with the vertices and not with cells. Next it is declared that each scalar is a float and that each scalar consists of only one number. It is possible to define custom lookup tables, but in this project only the default is used. Then in the order the vertices were defined, the corresponding scalar values are given.

This message is then passed to the *TabletVisServerConnection*, where it may be compressed. In that case the ending '|*end*|' is added to the compressed byte set, so that the client knows when the byte stream is finished. Then the data is transferred to the *TabletVisClientConnection*.

After all data was received, the *TabletVisClientConnection* passes the complete message to the *TabletVisClient*. If compression is activated, the *TabletVisServer* decompresses the message for further encoding. Then it is read which request was answered and the corresponding additional data is extracted. In case of a polygon set, VTK is used to read the serialized information.

The extracted data is then passed to the *TabletVisAppDelegate*. In case of a clipping request, the polygon set is transferred to the *TabletVisApp*, which updates the visual representation cut-plane node in the scenegraph.

Optional Compression

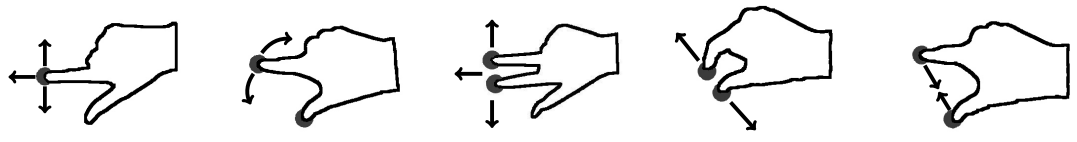
In order to reduce the amount of data that is transmitted from server to client, especially when large polygon sets are sent, the app can be set to compress these messages. Due to the fact that the amount of data sent from the client is usually small, the compression is only used in the direction server to client. The compressions is optional, i.e. the user can disable it at any time.

For this purpose [ZLIB] is used. An open-source, cross-platform library that enables lossless compression. It uses an LZ77 method called deflate, which is a type of dictionary coder combined with Huffman coding. This method is also used for the ZIP archive file format. It gives good compression results on different types of data while using few resources.

The compression can be set to levels from 0 to 9, while 0 means no compression and 9 is the highest level.

3.6 User Interface

The user can choose from a set of datasets to load. The standalone app provides the possibility to download files from Dropbox or via email, while the client-server app restricts the set of datasets to the ones stored on the server. For each dataset the surface of the dataset is shown. Furthermore there are three additional representations of the dataset which can be displayed simultaneously. In order to examine these additional representations with respect to the whole dataset, the surface of the dataset can be set to opaque, transparent or not to be rendered. In Figure 3.11 and Figure 3.12 the combination of different dataset representations with a transparent surface can be seen.



(a) Rotation (b) Rotation (c) Translation (d) Zoom in (e) Zoom out

FIGURE 3.10: The different touch gestures for rotation, translation and zoom.

The displayed content can be navigated with common touch gestures as depicted in Figure 3.10. There are two gestures for the rotation. With wiping gestures with one finger, as shown in Figure 3.10(a), the scene is rotated along an axis parallel to the screen. The direction of the finger movement is orthogonal to that rotation axis. In

order to rotate the object along the axis orthogonal to the screen, two fingers are used. As depicted in Figure 3.10(b), one touch is fixed and the other one describes a circular movement around it.

The translation of the scene is executed with wiping gestures with two touches, as depicted in Figure 3.10(c). The scene can be zoomed in by extending two touches, as in Figure 3.10(d). With a pinching gesture, shown in Figure 3.10(e), the scene is zoomed out.

The first additional representation is the cut-plane. There are two modes for the cut-plane: slice and clip. In slice mode, a cut-plane is displayed. Clipping results showing the surface of that part of the dataset that lies behind the cut-plane, see Figure 3.11.

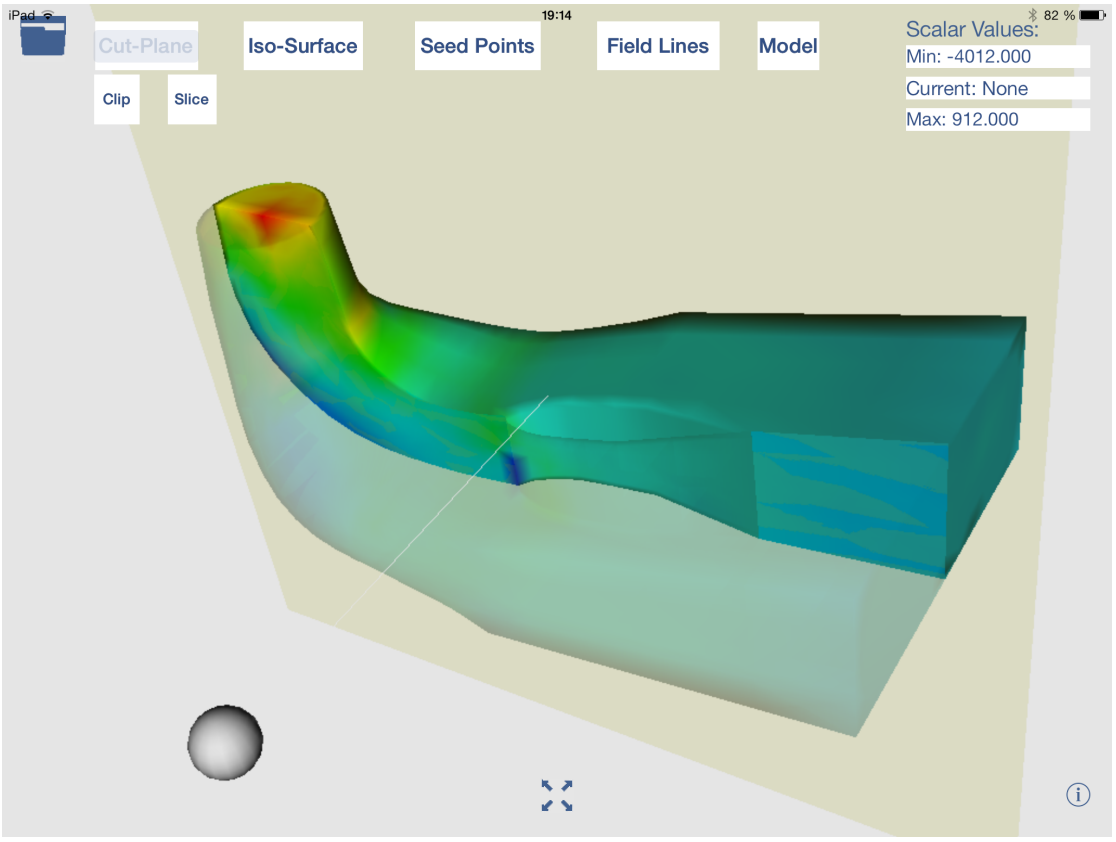


FIGURE 3.11: A clipping of the turbine dataset.

The positioning of the cut-plane is done with a plane widget. This widget consists of a plane and a normal with a small ball, see Figure **??**. The navigation gestures of the widget consist of two steps. The first touch selects either the normal or the plane. The selected item then turns green. Then a wiping gesture moves the widget. If the gesture starts with touching the normal, a rotation is initiated. A translation starts by selecting the plane.

The second representation is the iso-surface, which is used on scalar fields. The iso-surface connects points that have the specified iso-value similarly to the way that contour lines connect points of equal value or elevation. An example is shown in Figure 2.6.

For the extraction of iso-surfaces, the app offers eleven equidistant, scalar set specific iso-values, for which a surface can be shown. This method was chosen for demonstration purposes. In this way it is made sure that the chosen iso-value actually corresponds to a surface. To gain more flexibility it could be easily changed, so that the user can type in an iso-value directly.

The third representation consists of streamlines, see Figure 3.12. Streamlines are curves, which tangents follow the directions of the vector field. One streamline shows the path of a particle in a vector field. In order to compute a streamline, a seed-point has to be defined. This seed-point is then used as starting point for the computation. The *TabletVis* app supports only vector fields that are constant over time, i.e. vector fields at one given time.

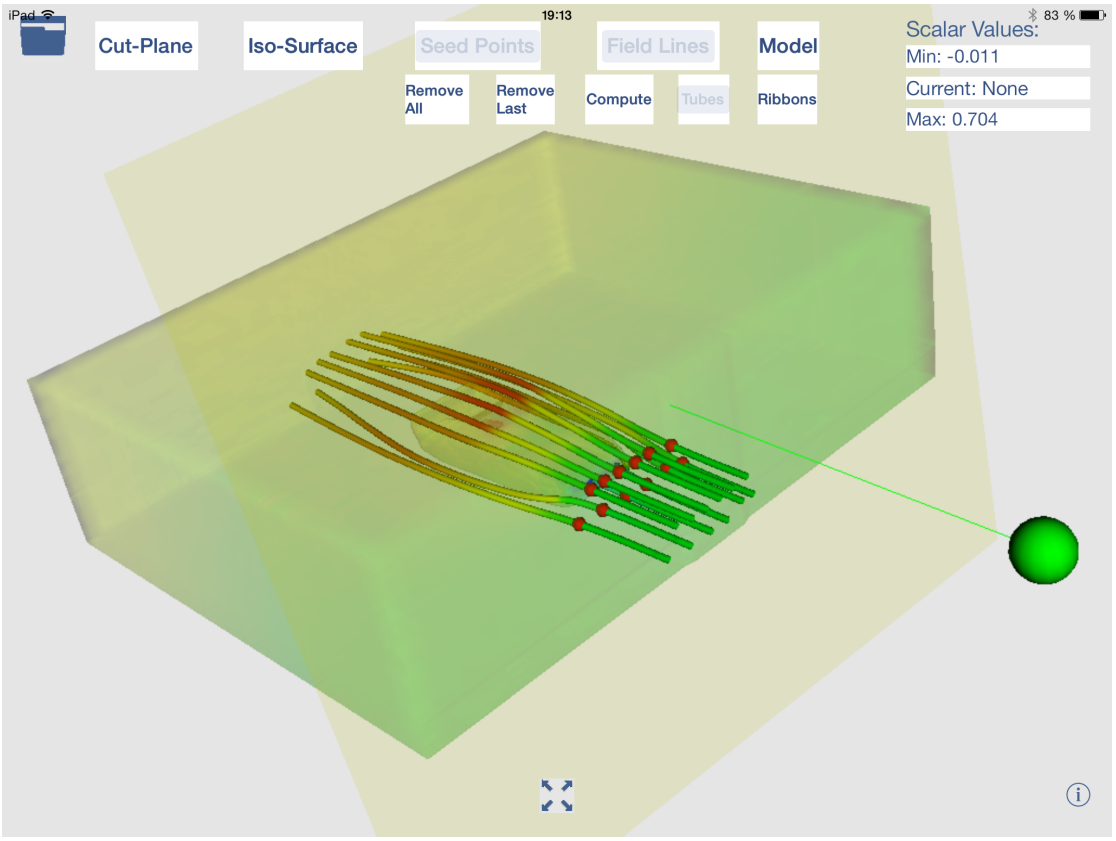


FIGURE 3.12: A set of streamlines of the car dataset.

The streamlines can be displayed in two modes, tubes and ribbons.

Seed-points are also set by using the plane widget. A double tap on the plane of the widget creates a seed-point at that exact position. It is then marked with a small red ball, as can be seen in Figure 3.12.

Chapter 4

Performance Testing

Scientific visualization usually requires dealing with large datasets. These datasets need to be processed in a reasonable time to ensure interactivity. In order to explore the possibilities and limitations of both the standalone and the client-server version of the *TabletVis* app, three experiments were conducted.

For this project, an iPad 4 (model MD511FD/A) equipped with a 1.4 GHz Apple A6X processor and 1GB RAM was used. The server was implemented on an iMac equipped with a 3,4 GHz Quad-Core Intel Core i5 processor and 2 times 4GB RAM.

This chapter begins with a short introduction of the five datasets used for the performance testing in Section 4.1. Then the three conducted experiments are described and their results given. In the first experiment, described in Section 4.2, some general time measurements of both the standalone and the client-server version of the app are taken. Then the client-server system and its different parts are examined in Section 4.3. At last the frame-rates of the standalone app are taken, which is described in Section 4.4.

4.1 Datasets

In order to get an overview of the behaviour of the *TabletVis* apps, five datasets of different sizes were selected for the experiments. Table 4.1 lists the basic properties of these datasets.

Table 4.1: Properties of the five datasets used for the experiments.

Name	Grid Type	Cells	Points	Attribute Data: Scalar	Attribute Data: Vector	Surface: Triangles	Surface: Vertices	File
Turbine	Unstructured	15 474	22 932	4	1	2 150	1 047	1.6 MB
Component	Curvilinear	43 008	47 025	3	1	15 616	8 262	1.7 MB
Noise	Rectilinear	117 649	125 000	1	1	28 812	14 408	13 MB
Carotid	Rectilinear	158 400	167 580	1	1	36 048	18 698	2.6 MB
Car	Unstructured	210 650	227 476	3	1	67 048	33 530	25 MB

The component, noise and carotid dataset were provided by VTK. The other two datasets were part of the [VISICADE] project. Visualizations of different representations of the datasets are given in Appendix A.

4.2 General Time Measurements

With this experiment a general overview is given over the timing of both the standalone and the client-server version of the *TabletVis* app. From the beginning of this project it was expected that the standalone version would reach its limits with larger datasets. That was the reason for implementing a client-server app. So this experiment should test that hypothesis.

There are several aspects that are examined with this experiments. First of all it should be determined whether any of the two applications can handle the processing of large scientific datasets. Moreover which version performs better for different dataset sizes or different visualization techniques. It is expected that the computation on the server is faster than on the tablet PC. But it is not clear how the transmission of data between server and client impacts the overall processing time, compared to the standalone version.

4.2.1 Experiment Setting

For each app version the following set of actions was executed alternately and its time measured:

- 5 times a cut-plane in slice-mode
- 5 times a cut-plane in clip-mode
- 5 times an iso-surface for 3 different iso-values

From all measurements of each action the average was taken in order to eliminate the influence of internal scheduling.

To ensure reproducibility, the cut-planes were all conducted with the widget in default position. Moreover the three iso-values were chosen from the pre-selected equidistant values. The computation of streamlines is difficult to reproduce with the same parameters. Therefore this part of the applications was left out for these tests.

It is obvious that comparing the results of different datasets for actions such as cut-plane or iso-surface extraction is difficult. For iso-surfaces the run time of the marching cube algorithm depends on the size and location of the iso-surface and the complexity of the underlying grid. Nevertheless the timing of these actions can still give an impression of the processing times.

All server client tests were conducted with a network band width of 54 Mbps and a compression rate of 2.

4.2.2 Results

Out of all tests, the clipping took the longest for all models. Besides that the results of the datasets differ a lot.

Turbine Dataset

For the turbine dataset the standalone version of the app was faster in all cases but the clipping test, see Figure 4.1. Although the server was faster in computing, processing and transmitting the data took longer in most cases. At the same time, the differences are very small and barely noticeable for the user.

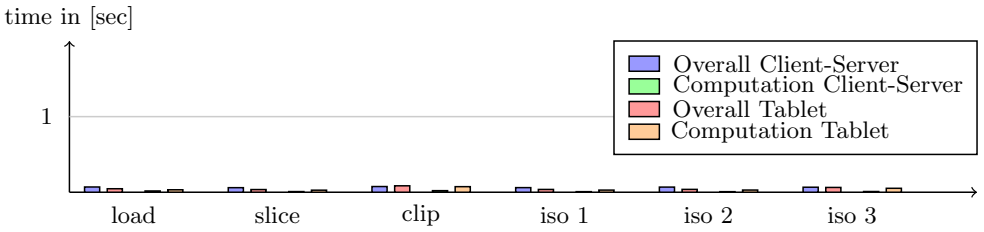


FIGURE 4.1: The results of the general timing tests with the turbine model.

Component Dataset

In Figure 4.2 it is shown that the client-server system was more than three times faster in the tests with the component dataset than the standalone version. That is due to the fact that the computations on the tablet took so much longer. In comparison to the noise dataset in Figure 4.3, which has more than 2.5 times more points and cells, the component dataset performs worse. The iso-surface times of different datasets are not comparable. But the component dataset takes almost twice as much time for the load and slice test with the client-server system. For the tablet version it takes about ten times as long as the noise dataset.

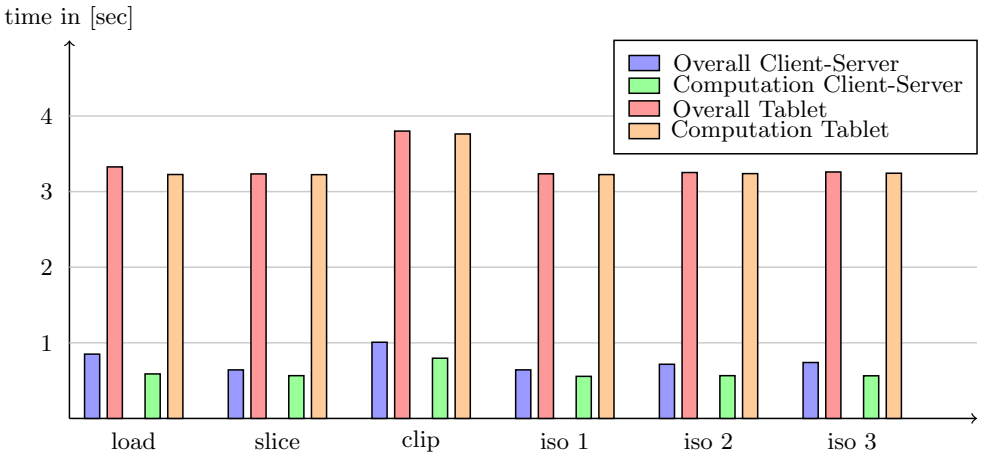


FIGURE 4.2: The results of the general timing tests with the component model.

Noise Dataset

For the noise dataset the server-client system is slightly slower than the standalone version in all tests but the clipping, see Figure 4.3.

Carotid Dataset

The longest computation times were measured for the carotid dataset, see Figure 4.4. The client-server system's computation times are more than five times faster than the tablet's. That results in overall processing times that are between four and five times faster.

Car Dataset

For the car dataset the client-server system performed slightly better for all tests, but the loading, see Figure 4.5. The clipping shows again a more significant difference between the two versions of the app.

It stands out how fast the standalone version can process this dataset. It is more than twice as fast as the processing on the component dataset. The differences are less noticeable for the client-server system.

Overall

In summary it can be observed that the client-server system is faster handling computationally intensive operations. That includes the processing of complex datasets, such as the carotid dataset, or methods such as clipping. That was expected. But it is also shown that the client-server communication does not impact the overall performance too much. Only for the turbine dataset and the faster computations of the noise dataset did the server perform a faster computation but the standalone version had a better overall processing. And in these cases the time difference was very small.

Moreover the impact of expensive operations is much higher in the standalone version of the *TabletVis* app. It did result in processing times of over 6 seconds for a clipping operation on the carotid dataset. The client-server version on the other hand did not take longer than 2 seconds in any test.

Furthermore it can be observed that the client-server system is not always faster than the standalone version, not even just for the larger datasets. For example for the turbine and the car dataset, the standalone version was faster loading the surface. The carotid and component dataset on the other hand, were loaded faster by the client-server application. A look into Table 4.1 shows, that neither the amount of cells, points, triangles and vertices of the surface nor the file size gives an indication on why the standalone version is sometimes faster and sometimes slower than the client-server version.

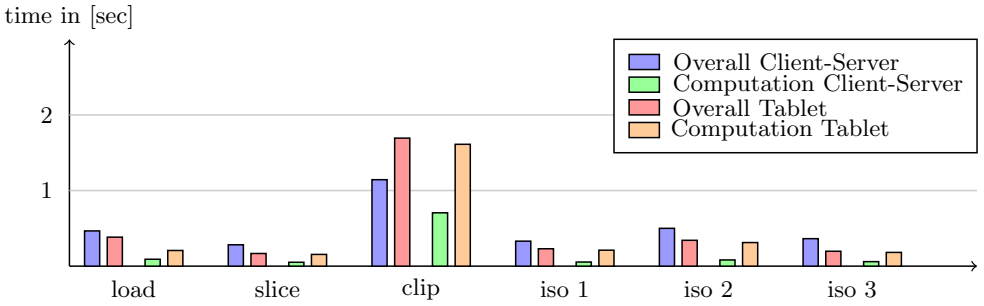


FIGURE 4.3: The results of the general timing tests with the noise model.

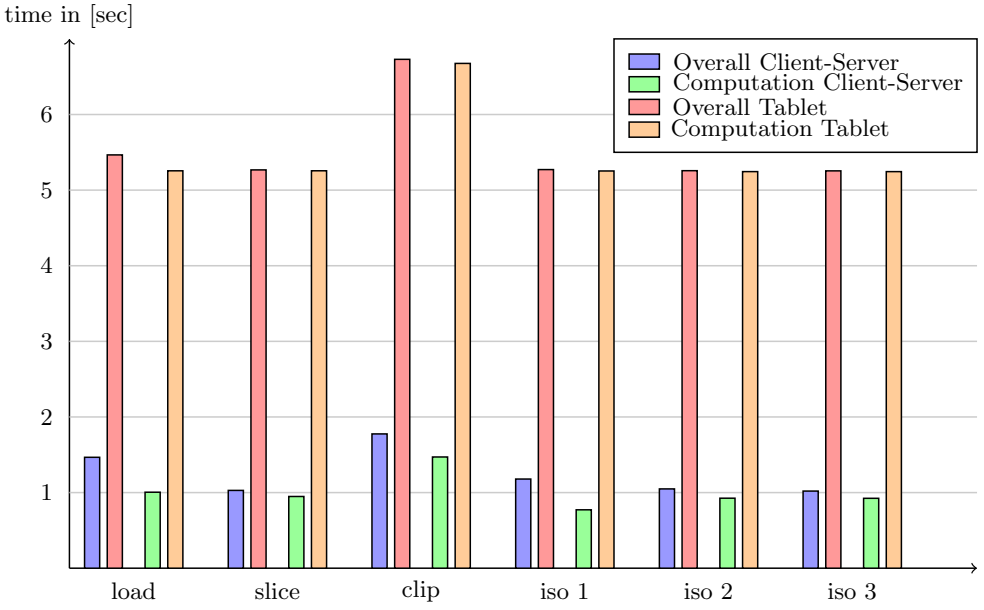


FIGURE 4.4: The results of the general timing tests with the carotid model.

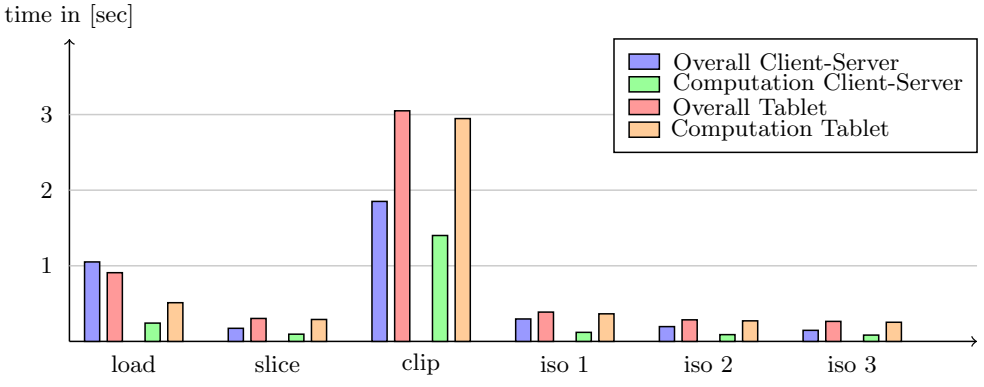


FIGURE 4.5: The results of the general timing tests with the car model.

But comparing the times of each version of the different datasets, it seems as though some datasets, for example the carotid and the component dataset, are computationally more intensive than others. And this complexity can not be read from basic information such as the amount of cells or in case of the surface extraction triangles or vertices.

4.3 The Client-Server Application

In the client-server app computationally intensive operations are transferred from the client to the server. This enables faster processing of bigger datasets. The aim of this experiment is to understand the influence of the different parts of the processing sequence in order to see if there is room for improvement. Moreover the influence of the compression level was examined.

For this experiment different parts of the loading process of a dataset were inspected. The loading process was chosen since its parameters are constant. That is useful for comparisons. Moreover it results in sending the whole surface of the dataset, which is a large amount of data that is transmitted from server to client. That enables a better examination of the limitations of the transmission process.

This experiment was conducted both with ASCII and binary encoding of the transmitted polygon data. In the case of this project, the client could easily read binary data created on the server. But that might not be the case when using a different tablet type or a different server. So in order to get a good overview, the overall processing times of the experiments in ASCII mode are included in the results.

4.3.1 Experiment Setting

Alternately different datasets were loaded and for each four times were taken, see Figure 4.6. The overall time T_{C_1} represents the time from tapping a button to having the dataset displayed. The time of a request from the client T_{C_2} starts when the request string is sent up to the time the answer string is received. Additionally the overall server time T_{S_1}, from the moment a request string is received up to the time an answer is sent, was taken. The computation time T_{S_2} measures the time taken by the VTK dataset.

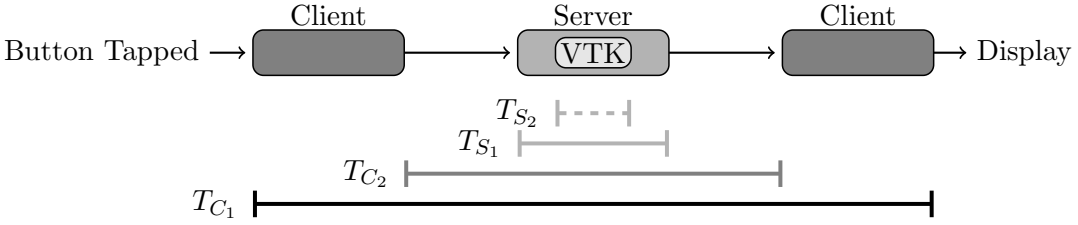


FIGURE 4.6: A schematic overview of the client-server experiments depicting the time spans that were measured.

The loading process was measured for ten different compression levels, where 0 means no compression and 9 is the greatest compression.

Since the processing time can vary due to side effects such as internal scheduling, each experiment was repeated five times. Moreover all experiments were conducted with a constant network band width of 54 Mbps.

4.3.2 Results

The detailed results are given in Appendix A. The graphs in Figure 4.7 are based on the averaged results.

In Figure 4.7 it can be seen that for the turbine dataset all time measurements from the binary experiments are between 0.01 and 0.1 seconds. So it is difficult to argue with this data, since conclusions from these small values are more error prone and less significant.

Client- and Server-Side Processing

The results for all datasets have several similarities. First the computing time is constant for all different compression levels. That was expected, since the parameters for the computation did not change. But the processing time of the client, which is depicted with the dashed red line, is also constant for all experiments, from level 1 on. That means that the time needed for the decompression is independent from the level of compression. Moreover the client-side processing time is similar for all datasets. The increase for larger datasets is only marginal.

Furthermore the overall server-side processing time shows a slight increase for all datasets beginning at level 0. Towards the higher levels, starting at level 5 or 6, the graph increases more and more. The larger the dataset have a steeper increase in the higher levels. This could be traced back to the fact that the compression becomes more time consuming for higher levels. And since the larger datasets tend to have larger data to compress, this factor weighs in more.

Transmission Time and Compression Rate

Another similarity is that the transmission time is also very stable for all datasets. After a subtle decline from no compression to compression level 1, the time for transmitting the data is almost constant. The larger the dataset, the larger the decrease is. Only the transmission time graph of the noise dataset and the car dataset show a slight increase in the higher compression levels. That can be explained by looking at Figure 4.8. First of all it can be observed that the amount of transmitted data drops significantly from level 0 to 1 for all datasets in both modes. The greater the starting amount is, the steeper the fall. And although the starting amounts differ for ASCII and binary mode of each dataset, from level 1 on the amount of bytes for the two modes are similar.

After compression level 1, the ASCII graphs and most binary graphs are slightly decreasing. Again the larger datasets such as the car dataset show a more noticeable decrease than the smaller datasets such as the turbine dataset. But it can also be observed that

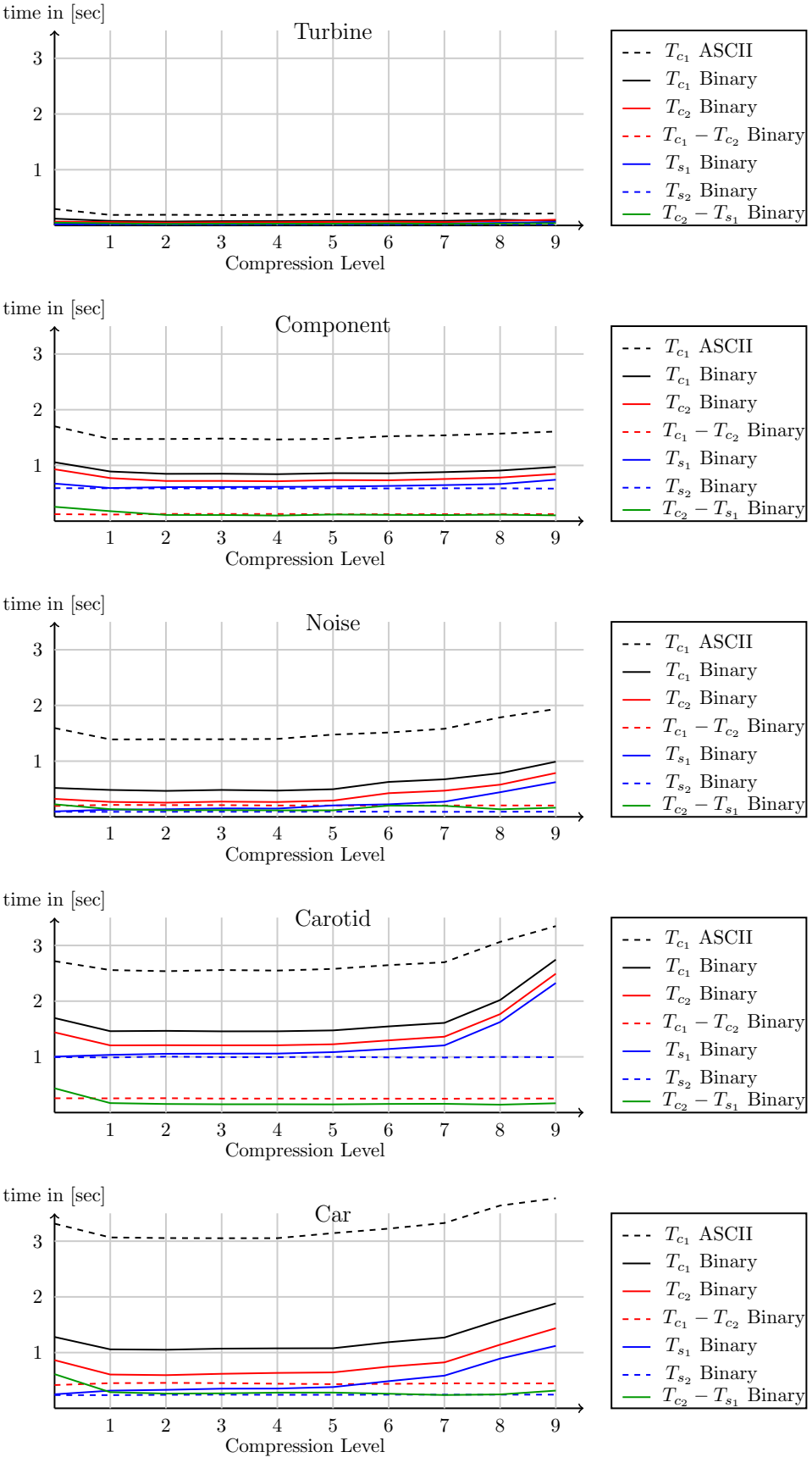


FIGURE 4.7: The results of the client-server tests.

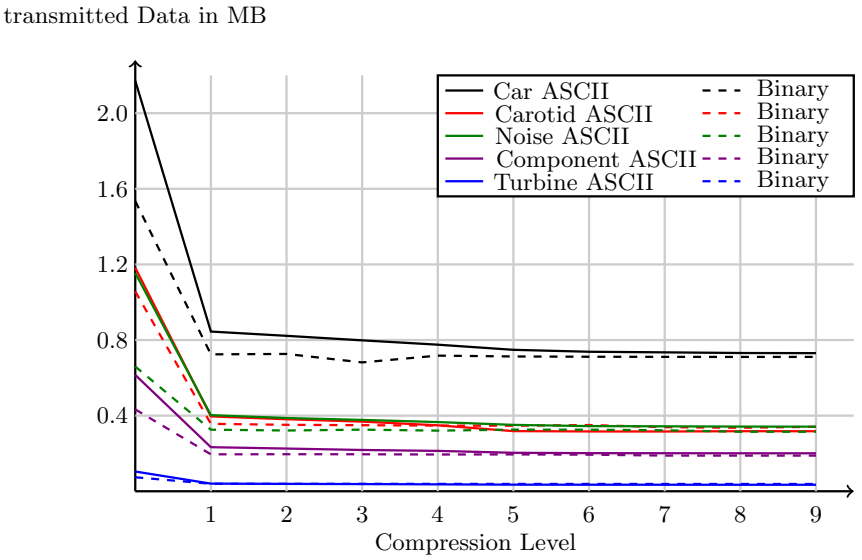


FIGURE 4.8: The amount of bytes transmitted per model in the client-server experiments.

the binary graph of the car dataset is slightly increasing from compression level 3 on. The binary graph of the noise dataset increases a little from level 4 on. That explains the slight increase in the transmission time in Figure 4.7. Overall the compression levels 2 and 3 give the fastest results. But at the same time the compression enhances the result only slightly, since the transmission time is not a big part of the overall loading time.

Overall it can be seen that the time to transmit data to the client is only a small portion of the overall processing time. For the smaller datasets such as the component dataset it ranges between 0.179 to 0.104 seconds for compressed binary data. The largest dataset, the car dataset, takes between 0.289 to 0.317 seconds for compressed binary data.

Overall

As noticed in the results from the first experiment in Section 4.2, it can be observed that the overall processing time for the loading of a dataset is not proportional to the amount of cells, points of a dataset or triangles and vertices of the surface. Although there is a tendency that larger datasets take longer to be processed, that does not hold for all datasets. The carotid dataset for example took longer to load than the car dataset.

It stands out that both the component and the carotid dataset have relatively high computing times, compared to the other datasets. The computation time takes up to two thirds of the whole loading time for these datasets, while the noise and car dataset spent less than half of the loading time on computation.

Furthermore it is noticeable that the transmission time is only a small part of the overall loading time. Moreover the compression and decompression of the data are

also negligible for lower compression levels. The time spent on computation is the determining factor for the processing time of the client-server application.

4.4 Frame-Rate

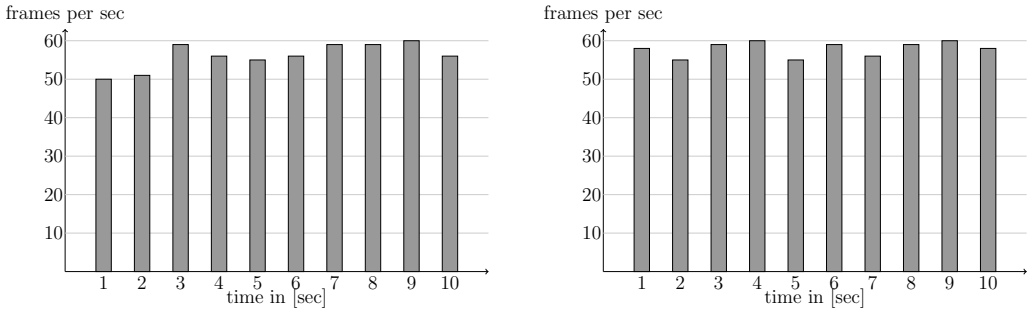
As described in Section 3.1 was that the scene should be rendered in real-time. In order to examine the rendering limits of the *TabletVis* app, the frame-rates of standalone app were measured. Since the client-server app is based on client-side rendering, there is no difference in the rendering capabilities of both app versions.

4.4.1 Experiment Settings

For this experiments the two largest datasets were used, the carotid and the car dataset. With each dataset a complex scene was created as depicted in Figure 4.10(a) and Figure 4.10(b). Then the scenes were rotated and the frame-rate was sampled.

4.4.2 Results

The results of the frame-rate experiment are shown in Figure 4.9.



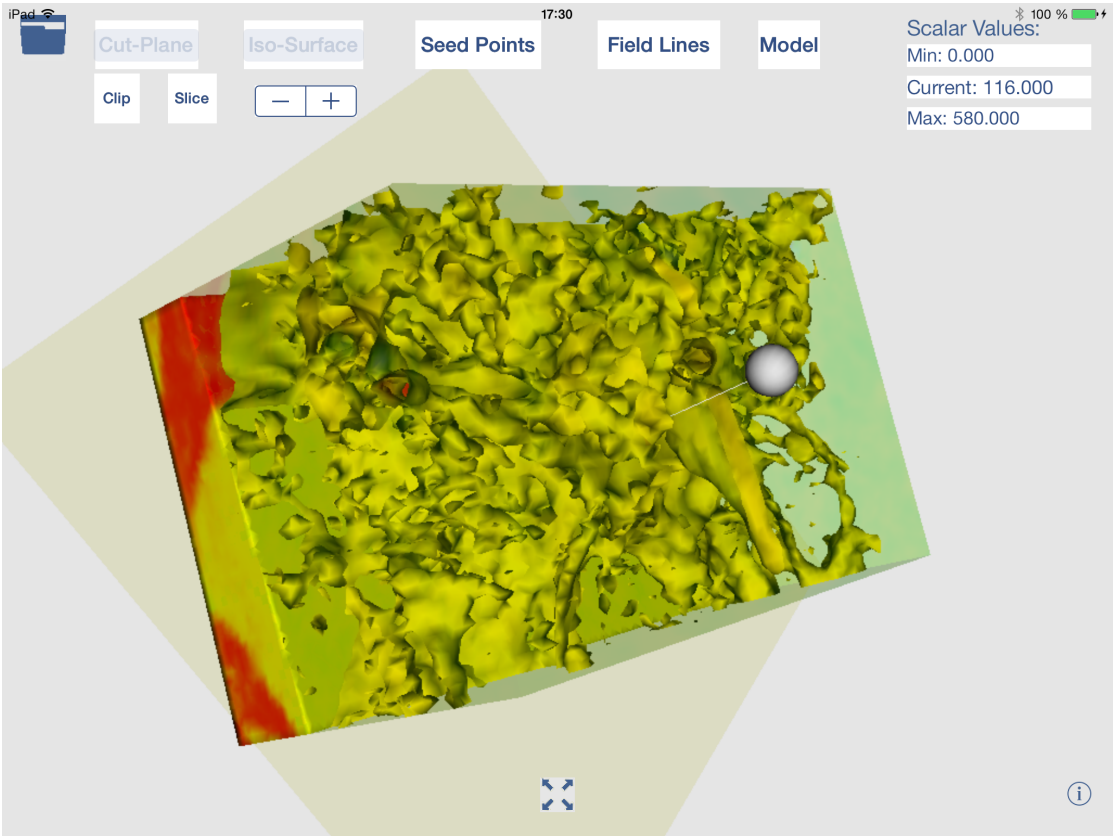
(a) Carotid (b) Car

FIGURE 4.9: The results of the frame-rate experiment.

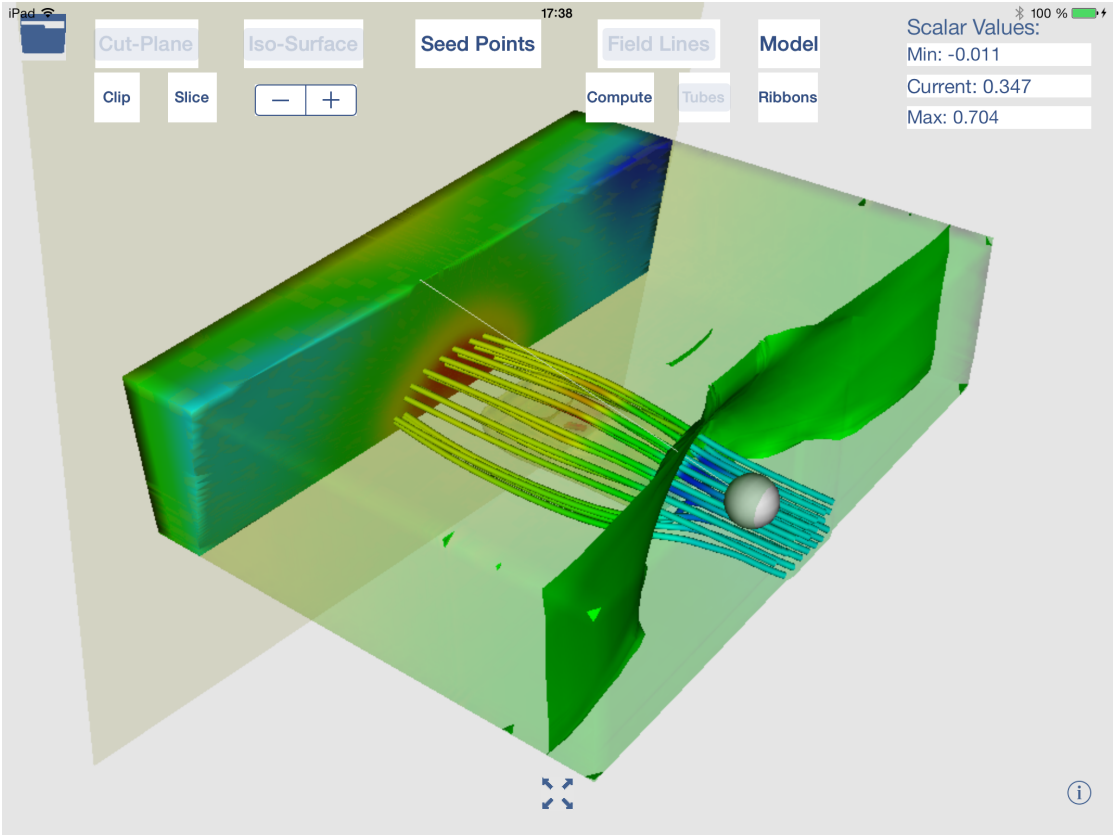
For the carotid dataset the average frame-rate during the test was 56.1 frames per second. It ranged between 50 and 60 frames per second.

For the car dataset the average frame-rate during the test was 57.9 frames per second. It ranged between 55 and 60 frames per second.

An application is said to be rendering in real-time if it displays more than 15 frames per second [AHH11]. From about 72 fps up, differences in the display rate are effectively not detectable. So a frame-rate of 55-60 fps is not only real-time, but also pretty good.



(a) The scene created with the carotid dataset consisting of 153 344 triangles and 78 670 vertices.



(b) The scene created with the car dataset consisting of 296 666 triangles and 149 077 vertices.

FIGURE 4.10: The two scenes used for the frame-rate tests.

Chapter 5

Usability Evaluation

Next to the technical suitability of tablets for scientific visualization, which was discussed in Chapter 4, the usability in terms of user interaction is equally important.

Compared to desktop applications for scientific visualization, the *TabletVis* app provides three new concepts for user interaction: the manipulation of the 3D model by touch, the touch manipulation of the plane widget and the tapping gesture for setting seed points. Hence the main focus of this chapter is the usability of these concepts.

Due to the time constraints of this project, most design aspects of the user interface, such as the layout, remained basic and did not become a priority. Therefore I abstained from extensive usability inspection, usability testing or comparisons to other established visualization systems.

Nevertheless a user study can give some insight on the app's usability and on existing problems. The aim of the conducted study is to examine the earlier mentioned new interaction concepts and to fathom the appeal of a scientific visualization application for tablets, irrespective of the appearance or design of the *TabletVis* app.

This chapter begins with an introduction of the term usability in Section 5.1. Next in Section 5.2 a short overview over evaluation methods for usability is given and it is explained which method was chosen for this project and why. Then the design and the design process of the utilized questionnaire is presented Section 5.3. Additionally the experiment setting is described in Section 5.4. This chapter finishes with a presentation of the results in Section 5.5.

5.1 What is Usability

Usability comes from usable and describes the "ability or fit to be used" [OD]. That is a very general description and it is not sufficient to cover all aspects of this quality with regard to user interfaces. Over the years there have been many attempts to find an adequate definition.

The International Organization of Standardization (ISO) defines usability as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [ISO9241].

The usability expert Nielsen gave the much-quoted definition, that usability is a "quality attribute that assesses how easy user interfaces are to use" [N12]. He extends the ISO definition to a list of five quality components:

Learnability How easy is it for users to accomplish basic tasks the first time they encounter the design?

Efficiency Once users have learned the design, how quickly can they perform tasks?

Memorability When users return to the design after a period of not using it, how easily can they re-establish proficiency?

Errors How many errors do users make, how severe are these errors, and how easily can they recover from the errors?

Satisfaction How pleasant is it to use the design?

5.2 Evaluating Usability

There are many different methods that are used to evaluate the usability of an interface. They vary in cost, complexity and at which time in the design process they are used.

In general one distinguishes between two types of usability evaluation methods, usability inspection and usability testing methods. Usability inspection methods are executed by usability experts who examine the user interface. In usability testing methods real, potential users test the interface and their behaviour and/or opinion is recorded.

Usability Inspection Methods

One of the most used inspection method is the heuristic evaluation. A usability specialist examines the interface with regard to a set of guidelines, the heuristics. The most popular heuristics are Nielsen's heuristics [N94].

Other widely exploited methods are cognitive or pluralistic walkthroughs [LW97]. In a cognitive walkthrough a usability expert reviews the interface by performing a specific task or use case step-by-step. In the pluralistic version not only a usability expert, but also a real user and a product developer perform the walkthrough.

The main advantage of expert-based usability evaluation methods is that less participants are needed to find more usability problems [N92]. Therefore these test are faster and potentially more thorough.

On the other hand real users may have different needs or problems than the expert imagines. So testing with experts only does not ensure to find all problems. Additionally it can be difficult to find usability specialists and they may be more expensive than a group of real users.

Usability Testing Methods

A widely used usability testing method is called thinking aloud [L82]. The user performs a specific task with the interface while saying out loud all of his thoughts. These thoughts and the steps taken in the interface are recorded and analysed later.

Usability testing also includes performance measurements that produce quantitative data. Popular measurements are for example the time to complete a specific task, number of user errors, time spent to recover from errors or the frequency of the use of the manual. The collected data can be used to compare different systems.

Another way of conducting a usability test is through interviews or questionnaires. After the user has performed a specific task with the interface, he answers several questions that are later analysed. The questions are often based on standardized test. In that way the results can be compared and a certain amount of reliability and validity is provided. While interviews allow for direct and individual questions, questionnaires are rigid but therefore enable structure an comparability.

The main advantage of user-based usability evaluation methods is that the opinions and problems of real users are detected. That increases the probability that the most important usability issues are found.

On the other hand the findings of each user are subjective and the validity of the overall result depends on the number of participants. A thorough test might need a lot of users which can be very time-consuming. Additionally some usability testing methods such as thinking aloud produce data that is difficult to analyse.

For this study a usability testing method was chosen. Since the main focus of the test are interaction concepts, such as touch gestures, the feedback of real users seems more valuable than an expert's opinion.

Using a questionnaire is the best choice for this project. It gives a good overview over the usability of the *TabletVis* app within a reasonable amount of cost and complexity. Moreover this method fits the time restrictions of this project.

The questionnaire, that is described in more detail in Section 5.3, is based on a standardized test, the System Usability Scale.

5.2.1 SUS - the System Usability Scale

The System Usability Scale (SUS) was developed in 1986 by John Brooke in order to give a global view of subjective assessments of usability [Brooke86]. It is kept very general so that it can be used for a variety of interfaces and systems. Moreover it also enables the test to be used for the comparison of different systems.

The SUS questionnaire consists of ten statements for which the agreement of the user is measured on a Likert Scale from 1 (strongly disagree) to 5 (strongly agree). In the original version, which was used for this project, the statements are phrased alternately in a positive and negative manner. The statements cover usability aspects such as the need for support, training, and complexity.

For the analysis of the collected data the answers to the questions are scaled to the interval [0,4]. That is done by subtracting 1 from the positive statements' scores and by subtracting the negative statements' scores from 5. Then the sum of all scaled scores is multiplied by 2.5 to get the SUS score that ranges between 0 and 100.

The SUS has been examined in several studies such as [TS04] or [BKM08]. The results imply that this scale is both valid and reliable and serves as a good measure for user satisfaction.

5.3 The Questionnaire

The questionnaire, given in Appendix B, starts with three questions that aim to assess the respondent's experience with mobile devices and scientific visualization software. Next nine questions are posed that are specifically about the *TabletVis* app. Then the ten SUS statements are given. At last the participants are asked to name aspects the liked or disliked.

The app-specific questions target those interaction features in which the *TabletVis* app differs the most from a system developed for a desktop PC. That includes the manipulation by touch of the 3D model, the touch manipulation of the plane widget and the tapping gesture for setting seed points.

The questions 4-12 are based on Nielsen's five quality components of usability, Section 5.1. Due to the experiment setting, memorability was not examined. Moreover the error handling was not explicitly tested. It was assumed that the most important aspects for these interaction features are covered by learnability (questions 4, 7, 10), efficiency (questions 5, 8, 11) and satisfaction (questions 6, 9, 12).

Since these questions are specific to this application, there were no standard surveys to derive them from. Therefore this part of the study has not been tested for reliability, validity, objectivity or sensitivity. Nevertheless the questions were designed following several guidelines which are supported by statistical evidence.

Alternating Positive and Negative Statements

Besides the SUS, many often used Usability questionnaires use both positive and negative phrasing. It is believed that this reduces the acquiescent bias, the tendency of a respondent to agree to everything, and the extreme response bias, the tendency to give extreme ratings. On the other hand one could argue that the alternation of positive and negative statements can lead to misunderstandings or mistakes by the respondent and to misinterpretation by the researcher.

In 2011 Sauro and Lewis published a study [SL11] comparing SUS scores conducted with only positive and with alternating positive and negative statements in an unmoderated setting. They concluded that there was no significant difference between the results obtained with the positive or with the original SUS questionnaire.

Given this result and the assumption that a small moderated study reduces the risk of misinterpretation by the respondents, the questioning is kept alternating. In this way the original SUS test can be used and the additional questions are in the same style.

The Number of Scale Points

An article by Finstad [F10] implies that 7-point Likert Scales provide a more accurate measure of the user's opinion than 5-point Likert Scales. However the benefits were considered small. At the same time the SUS, which is also part of the questionnaire for this project, uses a 5-point scale.

Since the results of Finstad's study give no indication on how the potential inaccuracy of the scale impacts the results of a study, the additional questions are supplied with 5-point Likert Scales.That ensures consistency with the SUS part.

Extreme Phrasing

In 2008 Karn et al. conducted a user study [KLNSKAN08] examining the influence of extreme phrasing in a user evaluation questionnaire. They found that extreme phrasings such as 'I think that this is one of my all-time favourite web sites.' or 'I thought the web site was very difficult to use.' lead to more extreme answers than moderate phrasings. Overall users tended to disagree more with extreme statements, both positive or negative.

With this result in mind, extreme phrases using words such as 'very', 'never', 'especially' or 'immediately' were avoided in the additional questions.

5.4 Experiment Settings

The model *carotid.vtk* used in the user study was provided by Kitware, Inc. via VTK. It contains a 3D scan of carotid arteries. Additionally it includes a vector field of flow data and a scalar field with speed values.

The experiment begins with a short introduction of the *TabletVis* app. Its features and the navigation are explained briefly using a manual.

Then the following task description is handed out and talked through.

Task Description

1. Open the *TabletVis* app
2. Choose model *carotid* to be displayed
3. Examine the model from all angles
4. Cut the model both with the *Clip* and the *Slice* method
5. Load iso-surfaces for a few different values
6. Place a few seed points and display the resulting streamlines both as tubes and ribbons

Afterwards the participant fills out the questionnaire that is given in Appendix B.

5.5 Results

The detailed answers to the questionnaire are given in the Appendix C, Table C.1. In Figure 5.1 the scaled and averaged answer scores a depicted.

Ten users participated in this user study. Out of these ten participants, six declared to have worked with scientific visualization software before. The list of software included ParaView, COVISE, VisIt, AutoCAD, OpenCover and genomic viewer. These six participants estimated their experience in visualization software on average with a score of 3 out of 4, i.e. *experienced*.

All ten participants declared to have used a smartphone or tablet PC before. The average estimated experience level was a score of 3 out of 4, i.e. *experienced*.

The scaled and averaged refers to the method with which the SUS is calculated. The scores of the negative statements are reversed by first subtracting 5 and then taking the absolute value. Then all scores are scaled to the range [0,4] by subtracting 1 from each. As a result the average scaled score for each question can be interpreted with 4 being the best and 0 being the worst value.

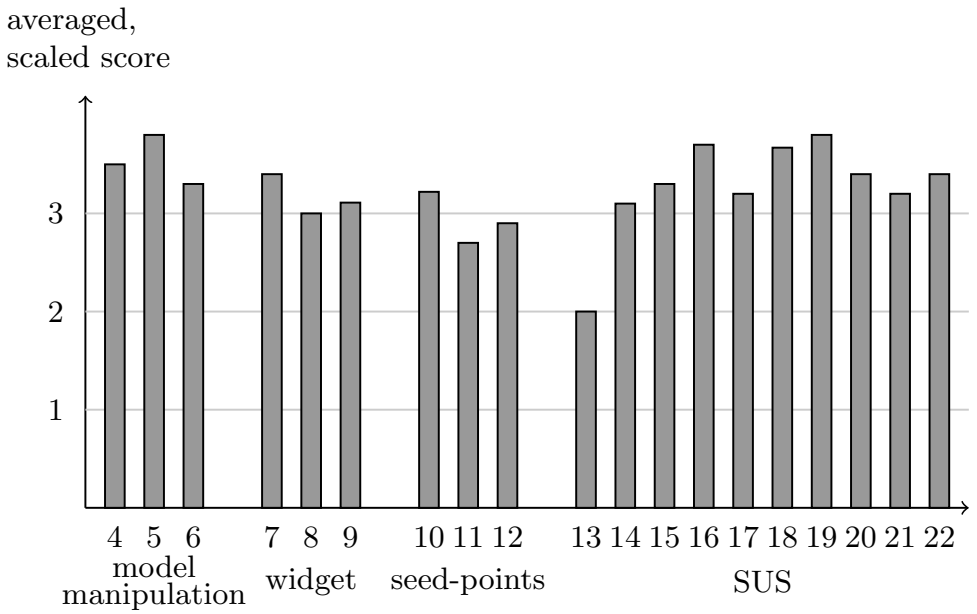


FIGURE 5.1: The scaled and averaged results of the questionnaire.

In Figure 5.1 it can be observed that out of the three examined interaction methods, the touch gestures for the model manipulation was rated best, with an average of 3.52 of the three questions. The widget got rated 3.17 on average and the seed-points got 2.94. For both the widget and the seed-point manipulation, the precise positioning was scored the worst.

For the SUS section, all results lie above three, but the first. That questions was whether the participant could imagine to use the *TabletVis* app regularly. Only 6 out of ten users answered this particularly question. Given that most participants did not come from a field of work where the *TabletVis* app could be used regularly, this score is not meaningful.

The highest ratings in the SUS section are for questions 16, 18 and 19. These questions were about needed support, inconsistencies and the learning speed of the app. This indicates that the participants in the study perceived the app as easy to learn.

The SUS score for this study amounts to 81.925. It is calculated by multiplying 2.5 to the sum of all scaled average scores of the questions 13-22. This number on its own is difficult to interpret, since the SUS is usually used to compare different systems or different versions of one system. Moreover the study was conducted with only ten participants. Bangor et al. compared 3,500 surveys in 273 studies to examine what an individual SUS score means, [BKM08]. They discovered that the median score of all surveys was at 70.5 and the fourth quartile ranged between 77.8 and 93.9. From that it can be deducted that a SUS score of 81.925 is above average and a good result.

5.5.1 Answers to Open Questions

The translated answers to the last two questions are given in Table C.2. The critique can be distinguished in four different parts.

Interaction Issues

The main interaction issue was the widget. It was said to be difficult to precisely navigate. For another user the widget lacked visual cues, that would indicate the options of navigation. Additionally it was mentioned that moving the model while displaying the widget was also difficult.

The second interaction issue was the loading time. The user tests were conducted with the standalone version of the app with a rather large model. Therefore the processing times of different operations were not interactive.

Additionally the simultaneous display of the model and some additional functionality lead to confusion. In one answer it was mentioned that when the participant first tapped the iso-surface button, the app did not behave as expected. Since the model was in *opaque* mode, the iso-surface was not displayed. The user did not know that setting the model to *transparent* or *not displayed* would have resolved the issue.

Requested Features

Some participants listed features they thought were missing or could be helpful. These requests included the following:

- the possibility to enter an exact iso-value
- an online help menu
- an *undo*-button
- a way of saving results, for example with a built-in screenshot functionality
- a button that resets everything, extending the *Home*-button such that all additional visualizations (iso-surfaces, streamlines,...) are deleted as well

Layout Issues

The positioning of the data menu button was found faulty. Moreover the overall UI-Design was listed as negative by one participant.

Positive Aspects of the Interface and the Interaction Possibilities

Overall the manipulation of the model via touch was received positively. It was described with terms such as 'familiar', 'intuitive', pleasant' and 'easy to understand'. Additionally several participants approved of the clearly arranged menu and the simplicity of the app. One user mentioned that the 'visualization algorithms are relevant' and that 'slicing, clipping, iso-surfaces and streamlines cover the whole spectrum'. Furthermore it remarked that it was positive that the app runs on a tablet and that the different functions could be used simultaneously.

Chapter 6

Conclusion and Future Work

6.1 Summary

This work discusses the use of tablet PCs for flow visualization. At first the fundamentals in scientific visualization, with the focus on flow fields, are introduced briefly. Then it is stated which requirements a system must fulfil so that it can be used to examine the potential and limitations of tablet PCs with regard to flow visualization. There are three requirements concerning the visualization: the ability to process flow field datasets, the availability of common visualization techniques and real-time rendering. Additionally it is required that the system should preserve the mobility of the device. Moreover the system should make use of the user interaction possibilities offered by the tablet PC, namely touch gestures and the gyroscope.

From these requirements the major design decisions are deducted. It is stated why the iPad was chosen as hardware and that the visualization is based on VTK. Furthermore it is explained that within the scope of this project two applications should be developed, one standalone version and one with local rendering and a client-server system. Next the design decisions concerning the user interaction are given. That includes a description of the failed attempt to utilize the gyroscope for navigation in the scene.

In the next sections the visualization libraries VTK, VES and Kiwi are introduced. Then the general design ideas, that both versions of the application are based on, are briefly explained with regard to the concrete implementation. The first pattern is the delegation pattern which is used in the iOS main run loop. Secondly the model-view-controller pattern is used to structure the entire application. And thirdly there is the visualization pipeline, which is the main concept of all VTK-based libraries. These general ideas are then followed by detailed descriptions of the implementations of the two versions of the application, i.e. the standalone and the client-server version. That includes an explanation of the client-server communication and the optional compression. Last but not least the user interface is presented and explained in detail.

Then follows a description of the performance testing and its results. Three experiments are conducted. First some general time measurements of both versions of the application

are taken. Then the client-server system is examined in detail. At last the frame-rates of the standalone version are measured.

Additionally the usability of the application is evaluated. After shortly introducing the notion of usability and a brief review of usability evaluation methods, the method chosen for this project, a SUS-based questionnaire, is presented. After describing the experiment settings, the results of the test are discussed.

6.2 Conclusion

Overall the results of this project show that tablet PCs offer great opportunities for flow visualization. We developed a standalone system, i.e. wireless and independent from network connections, for tablet PCs that allows for the exploration of flow data sets with common visualization techniques. The system is capable of processing datasets with over 200.000 cells and over 220.000 points. Although the computation times are capable of improvement, even larger scenes are rendered in real-time.

In general the proposed user interaction methods were received well by the participants of the user study. It turned out that the plane widget needs more work in order to be more predictable and accurate. But overall the touch interaction was said to be 'familiar', 'intuitive' and 'easy to understand'.

The client-server version was developed in case the tablet PC was not able to handle larger datasets. And it has proven itself has a reliable and efficient extension. The local rendering seems to be a good balance for tablet PCs to improve processing time, while keeping the data traffic low. The client-server system performed evenly well for different datasets and decreased the processing time for computationally intensive operations significantly, compared to the standalone version.

6.3 Future Work

The applications created in this project can be used as a basis for further studies on flow visualization on tablet PCs. Due to the time restrictions of this project, there was not enough time to thoroughly optimize the interaction methods. Especially the plane widget has the potential to be a useful interaction tool. Additionally the client-server application could be extended for the use of several clients.

Moreover the use of a desktop PC as server, enables the use of more advanced visualization techniques, such as Line Integral Convolution (LIC), see Section 2.3. So far the LIC algorithms are not implemented to run with OpenGL ES. But the computations could be performed on the server and the output could be processed such that the tablet PC was able to render it. With that said, the use of LIC combined with touch gestures offers interesting interaction possibilities. For example the selection of regions, for which the resolution of the LIC texture should be increased.

Furthermore the application could be extended for other research fields such as medicine or biology. That would entail the implementation of other visualization techniques. And with other visualization techniques there might come new ways to utilize the touch and gyroscope interaction.

Appendix A

Results of the Performance Tests

TABLE A.1: The averaged and rounded results of the general timing tests.

Dataset	Task	Standalone: Overall T_1	Computation T_2	Processing $T_1 - T_2$	Client Side: Overall T_{C_1}	Request T_{C_2}	Processing $T_{C_1} - T_{C_2}$	Server Side (C.-Level 2): Overall T_{S_1}	Computation T_{S_2}	Transmission $T_{C_2} - T_{S_1}$
Turbine	load	0.0463	0.0326	0.0137	0.0695	0.0501	0.0194	0.0229	0.0168	0.0272
	slice	0.0356	0.0273	0.0083	0.0604	0.0362	0.0242	0.0111	0.0088	0.0251
	clip	0.0851	0.0737	0.0114	0.0754	0.0606	0.0148	0.0254	0.0209	0.0352
	iso 1	0.0371	0.0284	0.0087	0.0610	0.0483	0.0128	0.0111	0.0077	0.0372
	iso 2	0.0378	0.0290	0.0088	0.0681	0.0539	0.0142	0.0112	0.0075	0.0426
	iso 3	0.0635	0.0521	0.0114	0.0664	0.0504	0.0160	0.0160	0.0096	0.0344
Component	load	3.3264	3.2259	0.1005	0.8506	0.7224	0.1282	0.6129	0.5886	0.1095
	slice	3.2337	3.2240	0.0097	0.6420	0.6262	0.0158	0.5714	0.5655	0.0548
	clip	3.8003	3.7618	0.0385	1.0076	0.9234	0.0842	0.8252	0.7963	0.0982
	iso 1	3.2354	3.2250	0.0104	0.6424	0.6247	0.0177	0.5644	0.5565	0.0603
	iso 2	3.2521	3.2376	0.0145	0.7164	0.6655	0.0509	0.5780	0.5656	0.0875
	iso 3	3.2593	3.2427	0.0166	0.7397	0.7073	0.0324	0.5803	0.5639	0.1270
Noise	load	0.3834	0.2072	0.1762	0.4658	0.2548	0.2110	0.1357	0.0912	0.1191
	slice	0.1673	0.1551	0.0122	0.2824	0.1004	0.1820	0.0609	0.0513	0.0395
	clip	1.6931	1.6114	0.0817	1.1434	0.9434	0.2000	0.7646	0.7054	0.1787
	iso 1	0.2299	0.2109	0.0190	0.3305	0.1448	0.1857	0.0738	0.0543	0.0710
	iso 2	0.3417	0.3119	0.0298	0.5002	0.2991	0.2010	0.1384	0.0821	0.1607
	iso 3	0.1969	0.1817	0.0152	0.3633	0.1730	0.1903	0.0856	0.0595	0.0874
Carotid	load	5.4657	5.2554	0.2103	1.4666	1.2090	0.2576	1.0555	1.0047	0.1535
	slice	5.2674	5.2558	0.0116	1.0287	1.0074	0.0213	0.9478	0.9484	0.0596
	clip	6.7296	6.6757	0.0539	1.7758	1.6770	0.0988	1.5203	1.4708	0.1566
	iso 1	5.2716	5.2531	0.0184	1.1790	1.1265	0.0525	0.9678	0.772	0.1587
	iso 2	5.2570	5.2448	0.0123	1.0486	1.0220	0.0266	0.9419	0.9257	0.0801
	iso 3	5.2546	5.2446	0.0100	1.0199	1.0031	0.0168	0.9301	0.9242	0.0730
Car	load	0.9087	0.5118	0.3969	1.0511	0.5952	0.4559	0.3310	0.2422	0.2641
	slice	0.3036	0.2901	0.0135	0.1732	0.1514	0.0217	0.1067	0.0955	0.0447
	clip	3.0496	2.9470	0.1027	1.8514	1.7006	0.1508	1.4818	1.4005	0.2188
	iso 1	0.3877	0.3648	0.0229	0.2968	0.2465	0.0503	0.1498	0.1197	0.0967
	iso 2	0.2854	0.2720	0.0134	0.1957	0.1644	0.0312	0.1046	0.0896	0.0598
	iso 3	0.2647	0.2532	0.0116	0.1464	0.1300	0.0164	0.0900	0.0835	0.0400

TABLE A.2: The averaged and rounded results of the client-server tests using the turbine model in ASCII mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	0.295	0.080	0.214	0.024	0.018	0.057	13.3718
1	0.188	0.064	0.124	0.029	0.020	0.034	5.1774
2	0.191	0.067	0.124	0.027	0.017	0.040	4.9934
3	0.186	0.061	0.125	0.029	0.018	0.032	4.8506
4	0.190	0.066	0.124	0.028	0.017	0.037	4.6864
5	0.201	0.076	0.126	0.032	0.017	0.037	4.4686
6	0.196	0.071	0.126	0.038	0.018	0.033	4.4360
7	0.214	0.088	0.126	0.043	0.017	0.045	4.4177
8	0.206	0.081	0.125	0.051	0.017	0.029	4.4004
9	0.215	0.090	0.125	0.056	0.017	0.034	4.3998

TABLE A.3: The averaged and rounded results of the client-server tests using the turbine model in Binary mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	0.085	0.068	0.017	0.019	0.017	0.049	9.4769
1	0.081	0.061	0.021	0.023	0.017	0.038	5.0790
2	0.070	0.050	0.019	0.023	0.017	0.027	5.0363
3	0.077	0.057	0.020	0.024	0.017	0.033	5.0469
4	0.078	0.058	0.020	0.026	0.018	0.032	4.9875
5	0.082	0.063	0.019	0.026	0.018	0.031	4.9600
6	0.085	0.065	0.019	0.028	0.017	0.037	4.9598
7	0.082	0.060	0.021	0.032	0.018	0.029	4.9351
8	0.101	0.080	0.021	0.046	0.018	0.034	4.9323
9	0.121	0.102	0.019	0.062	0.017	0.040	4.9296

TABLE A.4: The averaged and rounded results of the client-server tests using the component model in ASCII mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	1.702	0.939	0.763	0.613	0.587	0.326	78.7615
1	1.475	0.766	0.710	0.641	0.594	0.125	29.8473
2	1.474	0.760	0.714	0.631	0.582	0.129	28.9150
3	1.482	0.768	0.713	0.650	0.591	0.118	27.9572
4	1.466	0.754	0.712	0.644	0.586	0.110	27.3364
5	1.478	0.763	0.715	0.668	0.588	0.109	26.0537
6	1.524	0.812	0.712	0.700	0.585	0.112	25.8041
7	1.540	0.827	0.713	0.712	0.584	0.115	25.7667
8	1.571	0.858	0.714	0.751	0.587	0.106	25.7217
9	1.608	0.894	0.715	0.773	0.585	0.120	25.7094

TABLE A.5: The averaged and rounded results of the client-server tests using the component model in binary mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	0.891	0.773	0.118	0.594	0.590	0.179	55.4023
1	0.849	0.721	0.129	0.610	0.587	0.111	25.0021
2	0.851	0.722	0.128	0.613	0.589	0.110	25.0852
3	0.843	0.716	0.128	0.615	0.587	0.100	25.0504
4	0.861	0.737	0.124	0.619	0.590	0.118	24.9010
5	0.858	0.733	0.125	0.632	0.587	0.112	24.9574
6	0.880	0.756	0.124	0.647	0.590	0.109	24.7793
7	0.908	0.782	0.127	0.666	0.589	0.115	24.1636
8	0.973	0.847	0.126	0.743	0.584	0.104	24.1454
9	1.057	0.931	0.125	0.674	0.592	0.257	24.1415

TABLE A.6: The averaged and rounded results of the client-server tests using the noise model in ASCII mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	1.594	0.508	1.087	0.134	0.093	0.374	147.7864
1	1.390	0.327	1.064	0.177	0.098	0.150	51.5372
2	1.393	0.327	1.066	0.178	0.095	0.148	49.5887
3	1.393	0.332	1.060	0.195	0.093	0.137	48.3140
4	1.399	0.332	1.067	0.191	0.093	0.140	46.8550
5	1.477	0.409	1.068	0.230	0.092	0.143	44.9493
6	1.514	0.449	1.065	0.304	0.092	0.145	44.1179
7	1.581	0.516	1.065	0.361	0.092	0.155	43.9684
8	1.785	0.718	1.067	0.573	0.092	0.146	43.7994
9	1.936	0.865	1.071	0.702	0.093	0.164	43.7380

TABLE A.7: The averaged and rounded results of the client-server tests using the noise model in binary mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	0.519	0.323	0.196	0.098	0.091	0.225	84.4497
1	0.483	0.268	0.215	0.129	0.090	0.138	41.6833
2	0.466	0.255	0.211	0.136	0.091	0.119	41.1390
3	0.483	0.273	0.210	0.152	0.092	0.121	41.7222
4	0.471	0.266	0.204	0.149	0.091	0.117	41.0604
5	0.496	0.292	0.204	0.205	0.093	0.117	41.7147
6	0.627	0.425	0.202	0.225	0.092	0.201	41.6890
7	0.674	0.470	0.204	0.272	0.090	0.198	41.2823
8	0.783	0.578	0.205	0.442	0.092	0.136	40.3105
9	0.990	0.787	0.203	0.623	0.092	0.164	40.3014

TABLE A.8: The averaged and rounded results of the client-server tests using the carotid model in ASCII mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	2.718	1.427	1.292	1.041	0.990	0.386	151.3562
1	2.558	1.263	1.295	1.083	0.986	0.180	50.6921
2	2.538	1.247	1.291	1.081	0.989	0.166	48.7715
3	2.559	1.261	1.298	1.101	0.987	0.160	47.1604
4	2.549	1.254	1.295	1.103	0.996	0.152	44.6632
5	2.579	1.290	1.289	1.140	0.999	0.155	40.7245
6	2.647	1.363	1.283	1.213	0.998	0.150	40.5021
7	2.698	1.407	1.290	1.270	0.993	0.137	40.4724
8	3.064	1.771	1.293	1.609	0.985	0.162	40.6726
9	3.347	2.053	1.294	1.885	0.995	0.167	40.6433

TABLE A.9: The averaged and rounded results of the client-server tests using the carotid model in binary mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	1.697	1.440	0.257	1.004	0.995	0.436	135.3265
1	1.461	1.206	0.255	1.036	0.989	0.170	45.6611
2	1.467	1.209	0.258	1.055	1.005	0.154	44.9949
3	1.458	1.207	0.251	1.058	0.994	0.149	44.7515
4	1.459	1.208	0.251	1.059	0.995	0.149	44.4559
5	1.475	1.226	0.249	1.085	1.000	0.147	44.3860
6	1.547	1.296	0.250	1.141	0.990	0.155	44.8397
7	1.610	1.362	0.248	1.206	0.987	0.157	43.3896
8	2.020	1.767	0.253	1.625	0.998	0.142	42.9829
9	2.745	2.493	0.252	2.326	0.994	0.167	43.6650

TABLE A.10: The averaged and rounded results of the client-server tests using the car model in ASCII mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	3.314	1.028	2.286	0.326	0.240	0.703	278.0156
1	3.067	0.747	2.321	0.408	0.244	0.339	108.1403
2	3.056	0.716	2.340	0.414	0.240	0.302	105.2489
3	3.053	0.726	2.328	0.444	0.236	0.282	102.1906
4	3.054	0.717	2.337	0.444	0.237	0.273	99.2549
5	3.144	0.810	2.334	0.521	0.238	0.271	95.7760
6	3.225	0.898	2.327	0.639	0.241	0.259	94.4658
7	3.326	0.987	2.339	0.720	0.235	0.267	94.0596
8	3.639	1.295	2.345	0.994	0.236	0.301	93.6151
9	3.770	1.427	2.343	1.140	0.235	0.287	93.5270

TABLE A.11: The averaged and rounded results of the client-server tests using the car model in binary mode.

Compression Level	Client Side: Overall O_c	Request R_c	Processing $O_c - R_c$	Server Side: Overall O_s	Computation C_s	Transmission $R_c - O_s$	Transmitted Data in kB
0	1.280	0.864	0.417	0.251	0.237	0.613	196.4740
1	1.058	0.606	0.451	0.317	0.236	0.289	92.7002
2	1.051	0.595	0.456	0.331	0.242	0.264	92.9802
3	1.071	0.619	0.452	0.352	0.245	0.268	92.1360
4	1.076	0.635	0.441	0.354	0.242	0.281	91.8414
5	1.078	0.644	0.433	0.381	0.242	0.282	91.2789
6	1.187	0.748	0.439	0.487	0.245	0.261	91.0854
7	1.270	0.824	0.447	0.586	0.245	0.238	90.9956
8	1.588	1.142	0.447	0.892	0.245	0.249	90.9631
9	1.883	1.437	0.446	1.120	0.245	0.317	90.9838

Appendix B

The Questionnaire

1. **How would you describe your level of experience with smartphones/tablets?**
   Wie würden Sie Ihre Erfahrung mit Smartphones/Tablet PCs einschätzen?

   ☐ **no experience** keine Erfahrung
   ☐ **little experience** wenig Erfahrung
   ☐ **experienced** erfahren
   ☐ **very experienced** sehr erfahren

2. **Did you already work with scientific visualization software?**
   Haben Sie schon einmal mit Software für Wissenschaftliche Visualisierung gearbeitet?

   ☐ **No** Nein
   ☐ **Yes, namely** Ja, und zwar _____

3. **How would you describe your level of experience with scientific visualization software?**
   Wie würden Sie Ihre Erfahrung mit Software für Wissenschaftliche Visualisierung einschätzen?

   ☐ **no experience** keine Erfahrung
   ☐ **little experience** wenig Erfahrung
   ☐ **experienced** erfahren
   ☐ **very experienced** sehr erfahren

4. **When moving the 3D model, the rotation and zoom behaved as I expected.**
   Beim Bewegen des 3D Models hat sich die Rotation und der Zoom verhalten wie von mir erwartet.

strongly disagree stimme überhaupt nicht zu			**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐	☐

5. It was difficult to manipulate the 3D model into the position I wanted.
Es war schwierig das 3D Modell in die von mir gewünschte Position zu bringen.

strongly disagree stimme überhaupt nicht zu			**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐	☐

6. The manipulation of the 3D model was straightforward.
Es war unkompliziert das 3D Modell zu rotieren/verschieben/zoomen.

strongly disagree stimme überhaupt nicht zu			**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐	☐

7. It was difficult to understand how I could control the plane widget.
Es war schwierig zu verstehen wie ich das Ebenen Widget kontrollieren kann.

strongly disagree stimme überhaupt nicht zu			**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐	☐

8. It was easy to manipulate the plane widget into the position I wanted it in.
Es war einfach das Ebenen Widget in die gewünschte Position zu bringen.

strongly disagree stimme überhaupt nicht zu			**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐	☐

9. It was unsatisfying to work with the plane widget.
Es war unbefriedigend mit dem Ebenen Widget zu arbeiten.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

10. It was easy to understand how I could set a seed point.
Es war einfach zu verstehen wie ich einen Startpunkt setzen kann.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

11. It was difficult to set the seed points exactly were I wanted them.
Es war schwierig die Startpunkte an genau den Stellen zu platzieren, wo ich sie haben wollte.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

12. Setting the seed points was straightforward.
Das Setzen der Startpunkte war unkompliziert.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

13. I think that I would like to use the *tabletVis* app frequently.
Ich kann mir sehr gut vorstellen, die *tabletVis* App regelmäßig zu benutzen.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

14. I found the *tabletVis* app unnecessarily complex.
Ich empfinde die *tabletVis* App als unnötig komplex.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

15. I thought the *tabletVis* app was easy to use.
Ich empfinde die *tabletVis* App als einfach zu benutzen.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

16. I think that I would need the support of a technical person to be able to use the *tabletVis* app.
Ich denke, dass ich technischen Support brauchen würde, um die *tabletVis* App zu nutzen.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

17. I found the various functions in the *tabletVis* app were well integrated.
Ich finde, dass die verschiedenen Funktionen der *tabletVis* App gut integriert sind.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

18. I thought there was too much inconsistency in the *tabletVis* app.
Ich finde, dass es in der *tabletVis* App zu viele Inkosistenzen gibt.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

19. I would imagine that most people would learn to use the *tabletVis* app very quickly.
Ich kann mir vorstellen, dass die meisten Leute die *tabletVis* App schnell zu beherrschen lernen.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

20. I found the *tabletVis* app very cumbersome to use.
Ich empfinde die Bedinung der *tabletVis* App asl sehr umständlich.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

21. I felt very confident using the *tabletVis* app.
Ich habe mich bei der Nutzung der *tabletVis* App sehr sicher gefühlt.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

22. I needed to learn a lot of things before I could get going with the *tabletVis* app.
Ich musste eine Menge Dinge lernen, bevor ich mit der *tabletVis* App arbeiten konnte.

strongly disagree stimme überhaupt nicht zu		**undecided** weder noch		**strongly agree** stimme voll und ganz zu	**don't know** weiß nicht
☐	☐	☐	☐	☐	☐

23. What did you like about the *tabletVis* app?
Was hat Ihnen an der *tabletVis* App gefallen?

.....

.....

.....

24. What did you dislike about the *tabletVis* app?
Was hat Ihnen an der *tabletVis* App nicht gefallen?

.....

.....

.....

Appendix C

The Results of the Questionnaire

The results are given for each participant.

Additionally the table contains the average and the scaled average for each question. For the questions 1 and 3 *no experience* translates to a value of 1 and *very experienced* to a value of 4. For the questions 4-22, *strongly disagree* relates to a value of 1 and *strongly agree* to a value of 5.

The scaled average refers to the method with which the SUS is calculated. The scores of the negative statements are reversed by first subtracting 5 and then taking the absolute value. Then all scores are scaled to the range [0,4] by subtracting 1 from each. As a result the average scaled score for each question can be interpreted with 4 being the best and 0 being the worst value.

TABLE C.1: The answers to the questionnaire, the average and the average scaled to the range [0,4].

	Participant:											
	1	2	3	4	5	6	7	8	9	10	average	scaled average
1	4	2	3	2	3	3	3	3	3	4	3	-
2	No	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	-	-
3	1	1	3	1	3	4	3	2	2	3	2.30	-
4	5	5	4	4	4	4	5	5	5	4	4.50	3.50
5	1	1	1	1	1	2	1	1	2	1	1.20	3.80
6	5	5	5	5	5	2	5	5	1	5	4.30	3.30
7	1	2	1	1	4	2	1	1	2	1	1.60	3.40
8	5	4	4	2	2	4	5	5	5	4	4.00	3.00
9	1	1	2	2	4	1	-	2	2	2	1.89	3.11
10	1	5	5	3	5	5	-	4	5	5	4.22	3.22
11	1	1	2	3	3	3	4	4	1	1	2.30	2.70
12	5	5	4	3	3	3	2	4	5	5	3.90	2.90
13	3	-	-	1	5	5	2	-	2	-	3.00	2.00
14	3	1	1	2	2	1	1	2	4	2	1.90	3.10
15	5	5	4	4	4	5	4	4	4	4	4.30	3.30
16	1	1	1	1	1	1	2	1	3	1	1.30	3.70
17	4	4	4	5	3	5	3	5	5	4	4.20	3.20
18	1	2	1	-	1	1	-	-	2	-	1.33	3.67
19	5	5	5	5	5	4	4	5	5	5	4.80	3.80
20	1	1	1	2	2	1	3	2	1	2	1.60	3.40
21	5	5	5	3	3	5	3	4	4	5	4.20	3.20
22	1	3	1	2	1	1	3	1	2	1	1.60	3.40

TABLE C.2: The answers to the open questions of the questionnaire, paired by participant.

What did you like about the *TabletVis* app?	**What did you dislike about the *TabletVis* app?**
clearly arranged, functional	UI-Design, loading- and waiting-times
precise view due to zoom, etc.	very complex
the possibilities of visualization, the iso-surfaces	
• using rotation, translation and zoom was intuitive • the visualization algorithms are relevant, slicing, clipping, iso-surfaces and streamlines cover the whole spectrum • it is positive that the app runs on a tablet	• the calculations are not interactive, it would have been nicer to have remote rendering • it should be possible to for example to enter the exact iso-value
navigation familiar from Touch-UI	widget gives only few visual cues
• manipulation of the model met expectations • simultaneous use of the functions • simplicity/clarity	• precise manipulation of the widget is difficult • display of the iso-surface unclear (transparency) *[when choosing the iso-surface while displaying the solid model, the iso-surface is not visible]* • waiting time: if I want to look at iso-value 0, I have to start at 5 and tap the stepper 5 times and wait • error correction *[for example an 'undo'-button]*
no sub-menus with sub-items, simple layout	a simple online-help would be good
clearly arranged menu , handling is easy to understand	the handling of the widget, it should be easier to rotate/translate the model including the widget
very pleasant and intuitive to use, it is easy to achieve the goal	• the folder-symbol could have been placed left or right at the bottom, the upper row is very crowded, there is plenty of space at the bottom • the functionality of the 'Home'-button is inconsistent: the widget is reset, but cut-planes and field-lines remain. How can you reset everything?
very intuitively operable	it should be possible to save the results

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