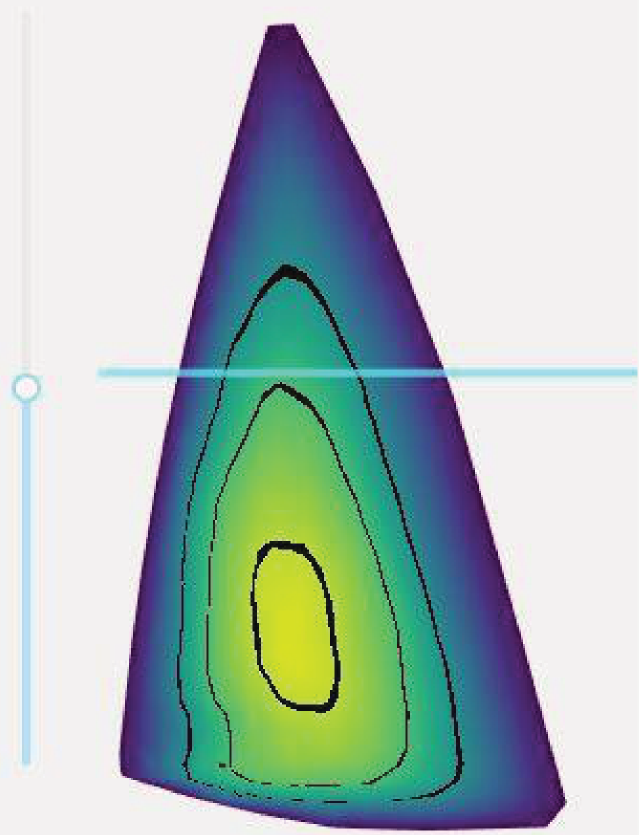
MSc thesis in Computer Science

Sail Shape Visualization

Danfeng Mu

2020



SAIL SHAPE VISUALIZATION

A thesis submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of

Master of Science in Computer Science

by

Danfeng Mu

January 2021

Danfeng Mu: *Sail Shape Visualization* (2021)

The work in this thesis was made in the:

Computer Graphics and Visualization
Department of Intelligent Systems
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology

Thesis Committee:	Dr. Ricardo Marroquim, TU Delft, supervisor
	Prof.dr. Elmar Eisemann, TU Delft
	Dr. Silvia Pintea, TU Delft
	Martin Kodde, Ingenieursbureau Geodelta B.V.
	Douwe Broekens, Sailing Innovation Centre
Student number:	5158516

ABSTRACT

While sailing, sailors solely rely on their eyes to inspect the sail shape and adjust the sail configurations to achieve an appropriate sail shape that corresponds to the weather condition. This so-called trimming process requires years of experience. Hence the visual inspection of sail shape suffers from inaccuracy and communication difficulties. Therefore, this research proposes a visual analysis tool that presents an accurate sail shape structure and supports sailors in investigating the optimal sail shape of certain weather conditions.

In order to achieve our goals, we reconstruct the sail shape using two triangulation methods. For incomplete reconstructed sail shapes caused by the uncertain image quality, we deform a complete template sail under the constraints of the incomplete sail shape and use the deformed sail as an estimation of the proper shape structure. We designed a visualization dashboard for sailors to explore the 3D structure, 2D profiles and characteristics of the time-varying sail shape and analyze their relation to boat speed.

The usability of the visualization tool is tested by a qualitative evaluation with two sailing experts. The result shows that the reconstruction and deformation of sail shape are valid, and the visualization dashboard has the potential to enhance sailors' comprehension of sail shape and provide insights into the optimal sail shape trimming.

ACKNOWLEDGEMENTS

To begin with, I want to thank my thesis advisor Ricardo Marroquim and my daily supervisor Marcos Pieras Sagardoy, who always give me valuable feedback on the thesis project during our regular meeting and provide me with insightful guidance on my thesis writing and who always being so kind and supportive during this a bit different corona study time. Next to this, I would like to thank Martin Kodde, Ardis Bollweg, Sjoerd Staats for all the help during my internship at Geodelta, you taught me a lot in different aspects. Moreover, I want to thank Douwe Broekens and other sailing athletes that participated in the sail shape data acquisition process for their excellent sailing skills and insights into the sail shape visualization project.

Furthermore, I would like to thank all my friends in Delft and my family for their accompany and support during my thesis.

Lastly, I want to thank all the readers for making the effort to read my report. I hope my thesis can provide you with the information you need.

CONTENTS

LIST OF FIGURES

1 INTRODUCTION

Thanks to the advances in the sport sensor technology, a large amount of data is generated, extracted and analyzed for different purposes. For example, Aisch and Quealy [2014] utilized the record of career touchdown of several famous Nation Football League players for public entertainment and Lommers [2015] used the road cycling descending data to aid athletes in achieving better performance. Sport data analysis also has the potential to innovate the traditional training routine and helps athletes better understand what factors are related to their performance.

Driven by the irruption of sport sensing technology and the eagerness of the coaches to have more knowledge on athletes' performance, a huge amount of data is collected. Nevertheless, in order to for athletes to understand and gain insights from the extracted data, appropriate approaches need to be applied and implemented. Due to the large quantity of the data, sport experts frequently turn to statistics, which lies at the core of the area known as *Sports Analytics*. But when athletes or sport experts do not know what to expect and want to explore the data, the statistical data can be confusing and misleading as it tends to summarize and show the overall data features. So, these standard statistics techniques might not apply to the acquired data and neglect some important features of the data. That is why statistics analysis are not always appropriate and enough for inspecting spots data.

Therefore the sports experts turn to visual analysis tool for exploring the data, thus sport data visualization has grown as a field. More and more attention is paid to this field, which can be proofed by IEEE Computer Graphics and Applications journal in 2016 (Basole and Saupe [2016]). In sport data visualization, data is presented to users in a more accessible and exploratory way, enabling users to form and test hypotheses upon them. Sacha et al. [2014] and Bertin [2015] also shows that sport visualization can convey more meaning and intriguer more insights than the traditional statistical measurement.

As one of the Olympics sports, sailing has always been of great interest and various sources of data are collected in this sport. van Hillegersberg et al. [2017] uses multiple sensor data like wind speed, boat heel angle to design a sailing analytic architecture and race evaluation dashboard. Taylor et al. [2016] use video camera and dinghy motion sensor to record athletes' motion and position on the sailboat. Apart from that, an active area of research in the sailing community is the sail shape analysis (Le Pelley and Modral [2008],Freides [1991],Deparday et al. [2016]) as the the shape of the sail is one of the key factors of sailing performance. Less optimal sail configuration might result in an inappropriate sail shape, thus falling behind during the race. Nevertheless, as will be discussed in this thesis, capturing the sail shape and analysing it are two very challenging tasks.

In practice, sailors try to set the sail of the boat and have an approximated idea of the orientation and strength of wind force, this process is called trimming in sailing terms. During sailing, sailors rely on their naked eyes to check the sail shape as trimming indication with the help of visual cues, like the stripes on the sail as shown in Figure 1.1a [1]. However, this visual inspection demands years of training experience from athletes to comprehend and master the control of the sail shape.

Apart from the requirement of years of experience, visual inspection of sail shape suffers from inaccuracy, as it is almost impossible for humans to have an exact visual measurement of the shape. Also, while sailing, the sail shape could change

1 https://www.uksailmakers.com/cruising-main-construction-options/draft-stripes

rapidly due to strong wind or sailor's control, making it hard to memorize the shape at different time instances. As a result of lacking accurate inspection of the sail shape, it becomes difficult for sailors to communicate the shape with other sailors or coaches and compare shapes to find the ones corresponding to the higher speed. Therefore, further investigating the relation between sail shape and sailing performance can lead to higher boat speed.

To address the issues of visual inspection of sail shape and help sailors understand the factors that affect the sailing performance, researches have been conducted to measure and analyse sail shape. There are two main trends in the sail shape analysis approach, the first one uses dynamometers to measure the pressure distribution across the sail while measuring the sail shape. Two examples of this trend are presented by Clauss and Heisen [2006] and Masuyama et al. [2009]. The use of dynamometer provides reliable sail shape and sailing performance measurement as the sail forces, sail shapes and wind conditions are acquired. But they mainly focus on their specific dynamometer boat on the upwind condition, and they do not provide a user interface for users to further explore and analyze the data.

The other trend is based on photogrammetry programs or image processing techniques to detect the shape of the sail by detecting the stripes of sails. Visual Sail Position And Rig Shape(VSPARS) which was proposed by Le Pelley and Modral [2008], combines image recognition technique and perspective-correction algorithm to visualize the shapes of sail stripes and the position of sail rig.

BSG Developements [2] has also developed their sail shape analysis tool called SailPack-Vision to visualize and measure the shapes based on the stripes on the sail using images as input. However, their systems require colored stripes to be painted or attached on the sail, and these stripes are assumed to be parallel to the horizon. This assumption may not always be true, Deparday et al. [2016] argues that the stripes of flying sails on a large range of apparent wind angles are not in a horizontal plane. Hence, they only define the sail shape based on the position of the stripes, which could lead to missing information on the complete sail shape. Apart from these issues, these systems do not analyse sailing performance data therefore do not relate sail shape to performance.

There is a variation of the second trend, instead of recognizing and recovering the stripes on the sail, Maciel et al. [2021] attach passive markers on the sailcloth and achieve sail mean shape during a time interval for sail design and analysis purposes. Though they could retrieve a complete sail shape, their research focuses more on the acquisition of sail shape than the analysis tool to aid sailors to improve their comprehension of sail shape and sailing performance.

An effective visualization for sail shapes and their relation to sailing performance has great potential to improve the traditional coaching routine, and help sailors gain more insights into the sail shape corresponds to better trimming in relation to the weather. Visualizing the sail shape goes beyond just rendering the 3D point cloud or an extracted surface from the point cloud. This project involves mapping important characteristics and metrics that might be visualized directly on the 3D sail shape, and developing abstract visualizations to aid in understanding the relation of the shape with performance.

In addition, Tahara et al. [2012] argues that the visualization of real-world sail shape in wind tunnel settings with performance data can also be used to validate the existing application of numerical simulations to predict sail performances.

The aim of this project is to reconstruct the three-dimensional shape of the sail for measurement and link it to performance data, so sailors and coaches can carry out a more informed trimming process. The name of the project is Digital Telltales, it consists of two parts, the first one is the sail shape data acquisition by using photogrammetry. The acquired sail shape data is in the form of 3D point cloud, these sail shape point cloud and sailing performance data are then utilized to develop visual designs to relate sail shape with performance. This thesis concentrates on the

2 http://www.bsgdev.com/CMS3/index.php

(a) Stripe on the Sail

(b) Data Acquisition Limitation Example

Figure 1.1: Sail Shape

latter part in collaboration with Geodelta[3], a company specialized in photogrammetry, who conducted the sail shape data acquisition part.

1.1 RESEARCH QUESTION

As mentioned in the previous section, a few sail shape measurement and visualization systems exist. But for the research using dynamometer boats, they only provide databases of the sail shape and sailing performance for their specific boat type without providing any analysis tool for sailors to further inspection of the sail shape and boat speed. For the research that uses photogrammetry or image processing program to measure sail shape, their visualized sail shape suffers from incompleteness due to only measuring the shape along the stripes. In addition, none of the methods present a visual analysis tool for sailors to investigate the optimal sail shape in relation to the weather condition. Therefore, the current sail shape analysis techniques are insufficient to support athletes to facilitate their sail shape trimming decisions.

This research aims to narrow this gap by designing a visualization tool to investigate and analyze the sail shape and sailing performance data to answer the question: *What is the optimal sail shape given a certain sailing condition?*.

In order to answer this question, we first need to achieve a reliable sail shape model from the point cloud data and then design an effective visualization dashboard to present the sail shape and sailing performance data for sailors to explore and discover which sail shape corresponds to higher boat speed.

To conclude, there are two main research questions we need to answer:

- How to reconstruct the 3D sail shape properly using the point cloud data?
- What visualization methods are perceived most useful for sailors to analyse the sail shape and sailing performance and enhance their sail shape trimming process?

1.2 APPROACH OVERVIEW

As mentioned in the introduction, the Digital Telltales project is formed by two parts: sail shape data acquisition and visualization.

Figure 1.2 shows the process of data acquisition and specifies the types of data that are involved, which are the image of the sail and corresponding point cloud

3 https://www.geodelta.com/en

and GPS locations. For obtaining sail shape data, coded markers are attached to the sailcloth, they are recognized by an image processing system. The position of the markers in 3D space is calculated by capturing two images of the sail that are simultaneously from a pair of calibrated cameras (known distance and orientation between them).

As we are only dealing with one boat, different trimming settings are tested and compared with their own sailing performance, in this project, the sailing performance is considered as the boat speed measured by a GPS.

The part of the project that was developed during this thesis includes two main parts: geometric data processing of the sail shape and the visualization design of the sail shape.

Figure 1.3 illustrates the pipeline of the sail shape data processing, the first step is the reconstruction of the sail shape from the point cloud data. Due to the uncertain image quality and occlusions from the sailor, it is not always possible to locate all the markers correctly, as shown in Figure 1.1b. The reconstructed sail shape might suffer from incompletion and accuracy issues. Therefore, a template sail shape is specified and it is deformed based on the current point cloud as an indication of the possible error.

The second step of the sail shape geometric data processing is the extraction of the sail shape characteristics. As the sail shape is reconstructed or deformed, the triangulation mesh can be used to extract the sail shape features. Sailors are used to viewing the sail shape based on the stripes on the sail, which in other words, are profiles of the sail. We can extract such profiles from the cross-section between the triangles and a horizontal line at a certain height of the mesh.

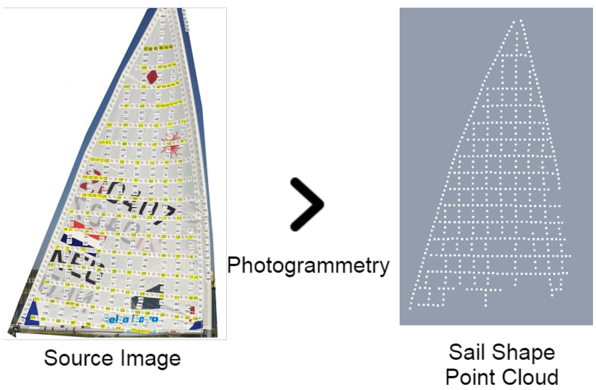


Figure 1.2: Data Acquisition

The final step of the research is to design the visualization dashboard to present different levels of details and show several features of the sail shape in conjunction with sailing performance data. In Figure 1.4 we can observe the round analysis of the visualization design dashboard, enabling users to inspect the sail shape and the sailing performance and context. After a round of training, users can see the boat speed of this period and explore the sail shape in terms of the 3D sail shape and its characteristics.

The comparison of the sail shape is shown in Figure 1.5, where the sail shape visualization and speed line chart are placed side by side (in number 8) and the profiles of the two shapes are overlaid (in number 9). By comparing the sail shape and their speed simultaneously, users have the ability to look into the relation between sail shape and boat speed.

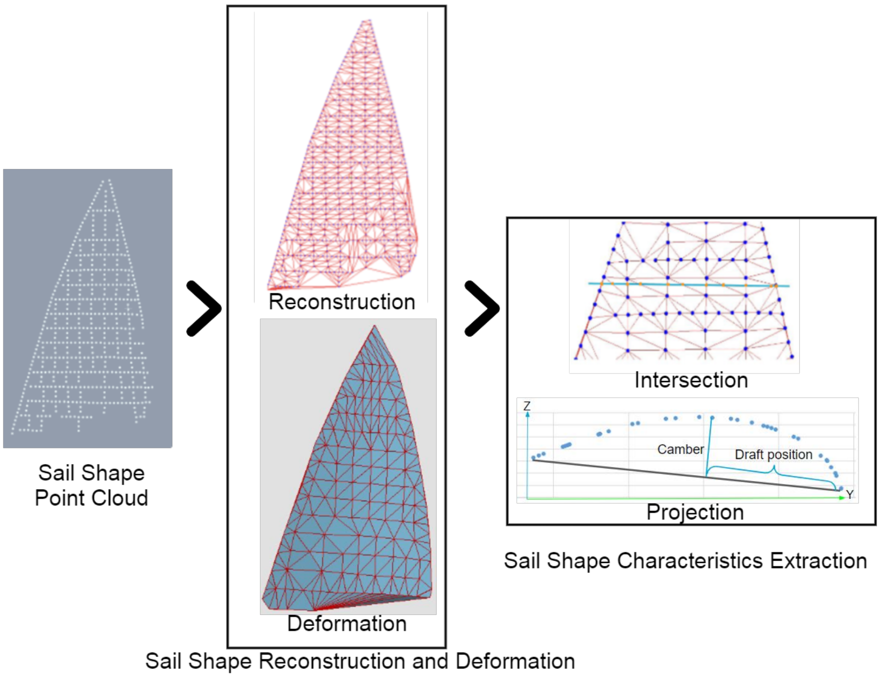


Figure 1.3: Geometric Data Processing

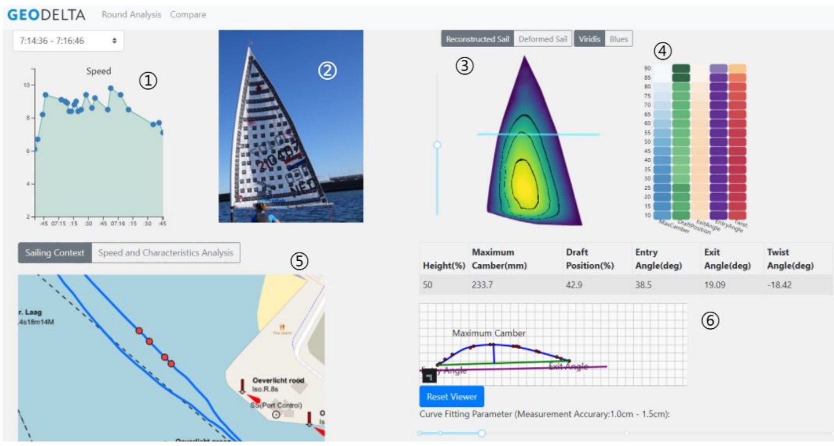


Figure 1.4: Sail Shape Round Analysis

1.3 THESIS OUTLINE

Here we explain the basic structure of this document, Chapter 2 introduces the essential background knowledge about sailing by first providing the fundamental physics behind sailing and then the terminology of sail shape and the definition of trimming.

Chapter 3 describes the data acquisition process and data format of the sail shape and sailing performance. The main visualization task is analyzed and elaborated based on the research question and data.

Chapter 4 presents the geometric data processing methods of the sail shape data, including the processing of the 3D sail shape and the sail shape parameter extraction.

Chapter 5 describes the proposed visualization approaches of the processed sail shape data and the sailing performance data.

Chapter 6 provides the evaluation of the visualization methods, including the user study with sailing experts and the result analysis.

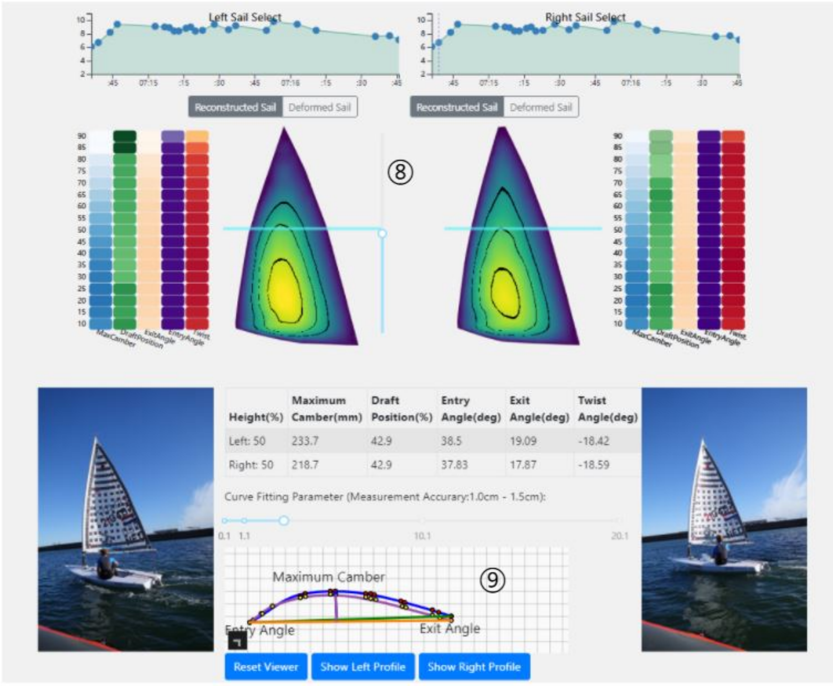


Figure 1.5: Sail Shape Comparison

Chapter 7 concludes this research and proposes the potential future direction.

2 SAILING BACKGROUND

The necessary sailing background and terminology related to this thesis are introduced in this chapter.

2.1 SAIL SHAPE TERMINOLOGY

In this work we have acquired data for a Laser sailboat as shown in Figure 2.1[1]. It is a type of boat in the Olympic dinghy sailing class. Considering the similarity of the dinghy sails, we assume that the methods and approaches in this thesis can also be applied to other dingy class sailboats. In Figure 2.1 the basic boat parts are labeled. The two sides of the sail are the *leech* and *luff*, and the luff is connected to the *mast* (the vertical pole of the sail). The pole at the bottom of the sail is the *boom* and the boat *hull* is where the sailor sits and controls the sail. Beneath the hull, there is the *keel* of the boat.

In Figure 2.2 (Aubin et al. [2016]), a profile curve of the sail shape is detailed, this would be equivalent to a stripe on the sail, as previously mentioned. The *maximal camber* is the largest depth from the curve to the chord (the connection line between luff and leech), while the *draft* position locates it on the chord. The *entry angle* is the angle between the curve and chord at the luff and the *exit angle* is the equivalent at the leech. The *twist angle* is the angle between the chord and the centerline of the boat hull. Alternatively, it can also be defined as the angle between the chord and the boom. In this thesis, we use the latter definition for the twist as we do not have any data regarding the orientation of the hull.

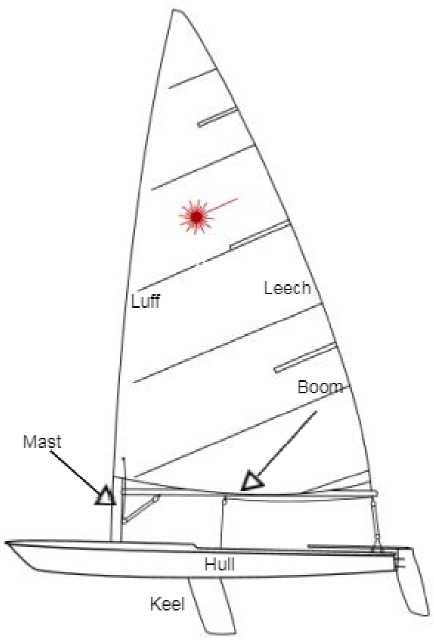


Figure 2.1: Sail terminology

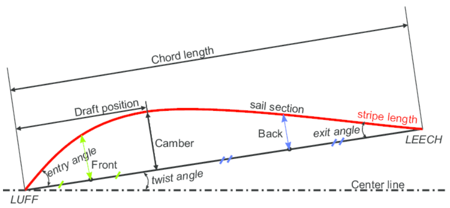


Figure 2.2: Stripe parameters of the sail

1 https://lasersailingtips.com/introduction/

2.2 THE PHYSICS OF SAILING

Sails harness wind energy with their aerodynamic shapes in the same way as airplane wings. Figure 2.3(c) illustrates how the sail generates lift based on Bernoulli's principle (Clancy [1975]). The air particles on the convex side have a longer distance to travel compared to the ones moving on the concave side. In order to finish their journey at the same time, the particles on the outer side need to have a relatively higher speed. Therefore, they have more room to spread out, resulting in lower pressure than the particles on the inner side. The difference between the air pressure generates the lift for the sail to move the boat.

However, the lift of the sail is pointing to the side of the boat, in order to prevent the boat from slipping sideways and help it to move in a certain direction, the keel comes to the stage. As shown in Figure 2.3(a), sail and keel produce lift forces in opposite directions and the vector sum of these lift forces, as shown in Figure 2.3(b), determine the moving direction of the boat. When the boat speed and course are constant the net lift force is balanced by the velocity-dependent drag force on the boat (Anderson [2008])

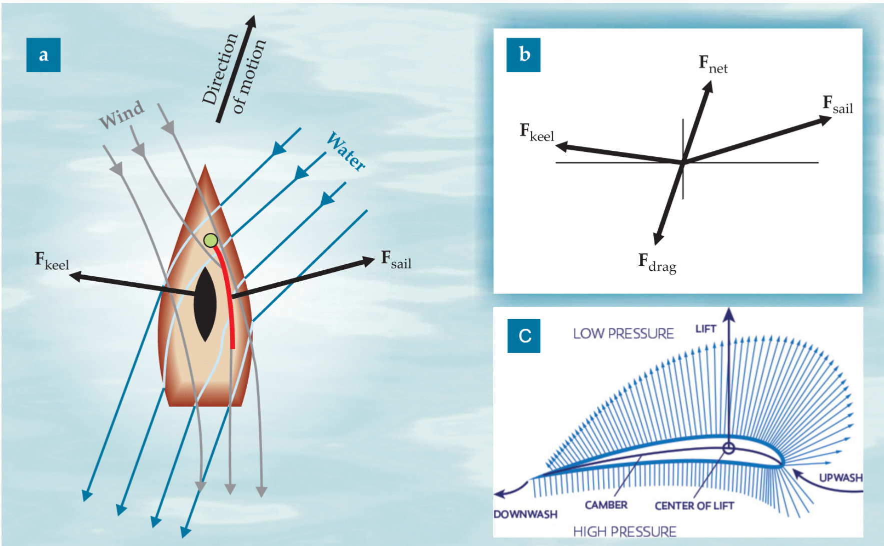


Figure 2.3: Physics of sail (modified from Anderson [2008]).

2.3 SAIL TRIM

When navigating, sailors use two indicators to determine whether the sail is under optimal settings (the angle of the sail corresponds to the wind direction): small strips of fabric that are attached to the sides of the sail, as shown in Figure 2.4, and stripes on the sail, as shown in Figure 1.1a. (Aubin et al. [2016]).

These fabric strips are called telltales and they are used for observing the wind flow around the sail. Based on the behaviors of telltales, sailors are able to decide what kind of sail shape should be applied to achieve higher speed and determine whether the current sail has achieved the optimal setting. The stripes provide information about the shape of the sail, which determines the amount of lift produced at a fixed angle of attack, which means the strength and position of the main driving force.

Controlling the sail to obtain the correct shape is called trimming. This process requires sailors to adjust the tension on the chords attached to the sail at the boom, luff and leech position, as shown in the Figure 2.1, to achieve a proper sail shape that corresponds to the sailing condition. For example, when sailors are sailing under

Figure 2.4: Telltales on the sail

heavy wind conditions, the sail needs to maintain a relatively more consistent and flat curved shape to catch the airflow when compared to sailing under light wind conditions.

3 VISUALIZATION DATA ANALYSIS

In this research, the visualization process follows a four-stage nested framework as proposed by Munzner Munzner [2014], as shown in Figure 3.1. These levels are not strictly nested but highly iterative due to the principles of problem-driven visualization design. The first stage specifies the domain situation, which encompasses a group of target users and their interests or questions.

In this study, the target users are sailors and coaches. They want to improve their comprehension of the sail trimming process to achieve better sailing performance. In order to reach this goal, they need to analyse the sail shape and sailing performance under different sailing conditions and find out the shape that can lead to a higher speed. To drill down their problem, they also have an interest in viewing the change between sail shapes with different trimmings so they can understand how the sail shape varies due to trimming.

After a set of meetings with sailing experts, we conducted the data abstraction. In this chapter we explain this process, we focus on explaining the domain question and elaborating the acquired data and its abstraction.

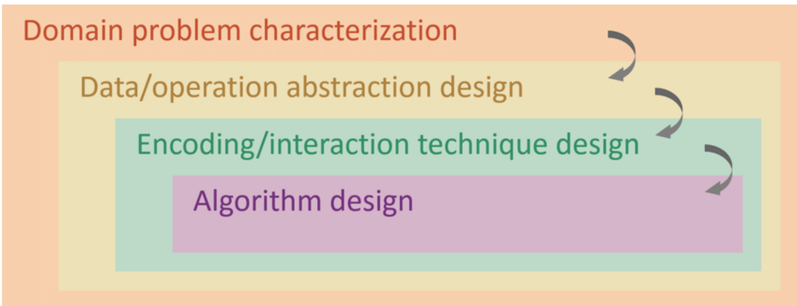


Figure 3.1: four-stage visualization framework

3.1 SAIL SHAPE DATA

While sailing, the sail shape is changing continuously due to various external forces, which makes the capture and measurement of sail shape challenging. In order to provide an accurate measurement of the sail shape, a photogrammetry rig was created by Geodelta to generate a 3D point cloud representation of the sail.

Holle [1982] acclaims that photogrammetry is the science and technology of obtaining reliable information about physical objects and the environment through the process of recording, measuring and interpreting photographic images and patterns of electromagnetic radiant imagery and other phenomena, which is also the basic concept of photogrammetry. Linder [2009] explains that it is a traditional part of geodesy and belongs to the field of remote sensing, but photogrammetry can be used for measuring a large variety of objects, especially when physical contact to the object is impossible. Photogrammetry can be realized with off-the-shelf cameras, offering a significant advantage in regards to methods that rely on more high-end devices. For the same reason, the setup is usually very flexible. Furthermore, fast moving objects, that are hard to capture with measuring devices that have slower response time, can be measured through photogrammetry by employing fast camera shutter times. For the above reasons, photogrammetry is a good candidate for measure flying sail shapes.

Photogrammetry contains various methods from different disciplines. As one variant of it, triangulation estimates the three-dimensional coordinates of points of an object based on at least two images of it that are taken at the same time but from different positions. In the Figure3.2, O_L and O_R are the focal points of two cameras. P_L and P_R are the respective projection of the point P in the images. The intersection of the line $O_L P_L$ and the line $O_R P_R$, which are rays from the focal point to the projection point on the image plane of the two cameras, determines the three-dimensional coordinate of the point P. The premises of this method are the position and orientation of the two cameras are measured.

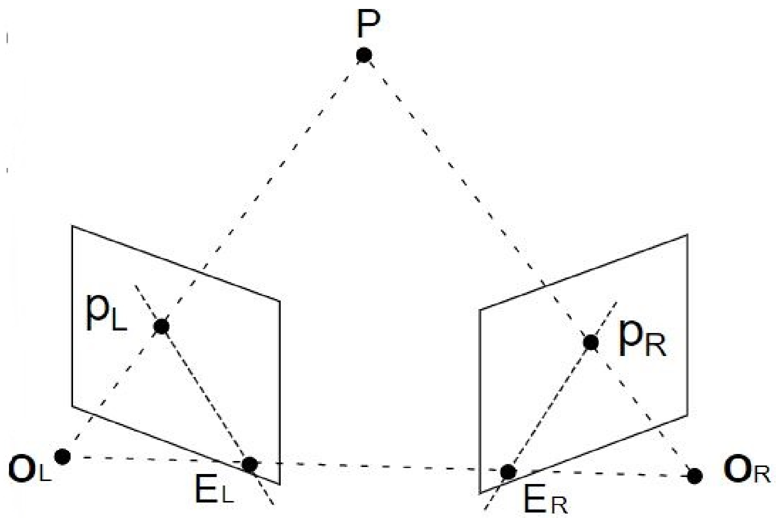


Figure 3.2: An example of stereophotogrammetry.

Basing on stereophotogrammetry theory, coded markers are attached to the sail for identifying the common points on the sail. This is necessary since the sail cloth is mostly homogeneous and does not have enough texture details to extract points to be triangulated. As shown in Figure 3.3, two types of the barcodes are used for the sail shape acquisition experiments. White barcodes, as shown on the left image, were attached to the sail for the preliminary onshore test and the first offshore test. However, after the first offshore test, we found the acquisition results were not satisfying as there were many barcodes that could not be detected. One of the reasons for the detection failure was the size of barcodes that were too small to be recognized in the images. Another reason was the strong sunlight reflection on the white background making the barcodes to be overexposed. Therefore, for the second offshore test, black background barcodes (shown on the right side) were glued to the other side of the sail with double the size of the first barcode (120mm per edge).

For acquiring the flying sail shape, a photogrammetry rig was built, as shown in Figure 3.5. The two Sony RX0 cameras are identical and the distance between them is 1.0 meter. Before the tests the camera were calibrated to retrieve their relative orientation. During the tests on the water, as shown in the Figure 3.6, a sailor would hold the acquisition devices from the coach boat and take photos of the training sailboat. In order to ensure the quality of the images, the coach boat needs to sail parallel to the training boat within 5 meters to achieve a barcode detection rate of at least 65

During the sail shape acquisition test on water, the acquisition frequency as 1Hz. If the capture process is automated in the future, the frequency could be controlled by the coaches. But for our experiments we found that 1Hz was enough to seize the small changes of the sail shape.

Figure 3.3: Two types of barcodes setting

In order to compare the performance of the sail shape with different trim settings, three trim settings were chosen for the test on water as shown in Figure 3.4:

- Loose trim setting, the sail shape has a relatively larger camber than other settings.
- Medium trim setting, the sail shape has an overall medium curvature.
- Tight trim setting, the sail is relatively flatter.

After the capturing session, the image pairs are processed by the image recognition program from Geodelta to detect the barcodes and compute their three dimensional coordinates if they are correctly detected in both images. Bundle adjustment is utilized in this process to improve the accuracy of the calculated coordinate value of the barcodes. The resulting sail shape data is listed as the barcode identification number and the X,Y,Z coordinate value of the center of that barcode measured in millimeters. A direct visualization of the raw sail shape point cloud data is shown in Figure 3.7.

In our study, the sail shape data (with black barcodes) that are acquired from the second test on the water are utilized. In total, there are 101 sets of sail shape point cloud and 59 of them are used as input to our visualizations after the prepossessing step, the rest are discarded because less than half of the total barcodes are detected.

3.2 SAILING PERFORMANCE DATA

Sailing performance in this study is defined as the boat speed, they are acquired by the GPS tracker that is placed on the sailboat while training. The resulting GPS data contains the following information:

- Acquisition time, which includes year, month, day, hour, minute and second data. The time data is used for the synchronization with the sail photos.
- Boat location, including the longitude and latitude data. They are used for visualizing the track of the training boat for providing the sailing context of the sail shape.

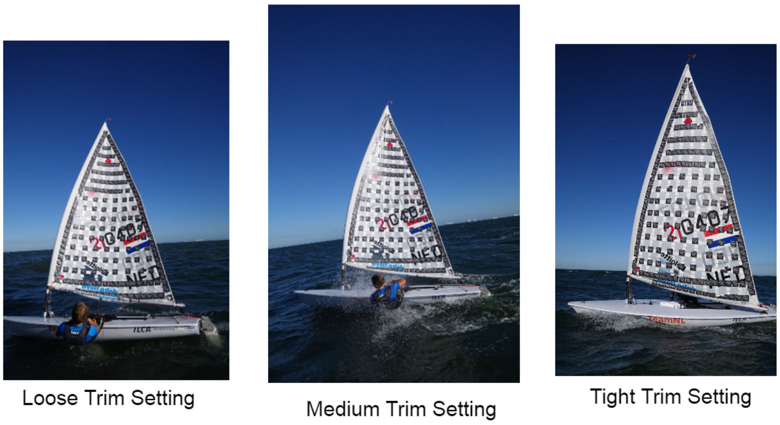


Figure 3.4: Three different trim setting

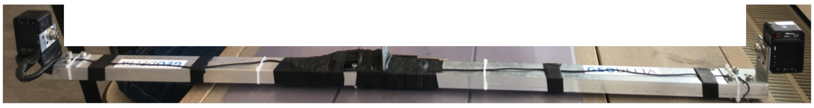


Figure 3.5: Sail shape acquisition device

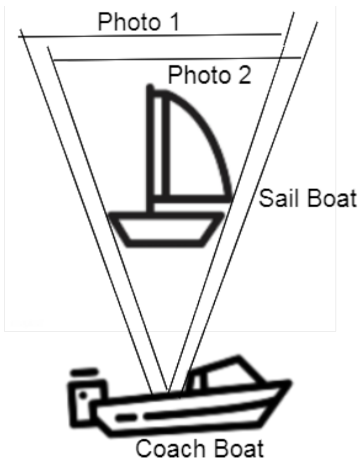


Figure 3.6: Sail shape acquisition setting

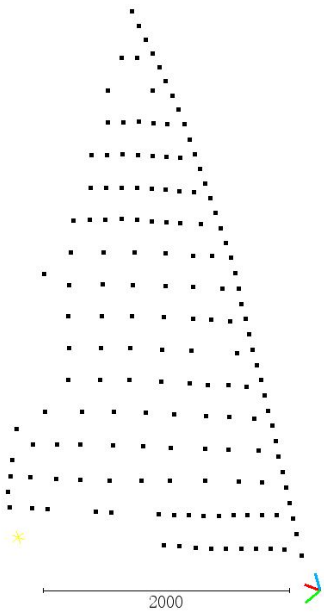


Figure 3.7: Sail shape point cloud

- Boat speed, shown as speed over ground (SOG). It is considered as the sailing performance data.

4 SAIL SHAPE DATA PROCESSING

As mentioned in Chapter 3, one of the main tasks of the visualization tool is the inspection of the sail shape, which includes inspecting the three-dimensional sail shape, the characteristics of the sail shape and the profiles of the shape.

In order to explore the sail shape in 3D space, it needs to be reconstructed from the sail shape point cloud. In Section 4.1, the process and algorithm for sail shape reconstruction are elaborated. The methods for extracting the sail shape characteristics are explained in Section 4.2 and the profile curve fitting algorithm is explained in Section 4.3. Finally, for incomplete sail shape, the extracted points are used as constraints to deform a template sail, which is proposed in Section 4.4

4.1 3D SAIL SHAPE RECONSTRUCTION

For the initial reconstruction of the sail shape from the point cloud, Delaunay triangulation (Delaunay [1934]) is applied as it maximizes the smallest angle in the resulting mesh, so skinny triangles can be avoided.

For understanding the above-mentioned advantages of Delaunay triangulation, the construction of it is shown in Figure 4.1(Commons [2020]). For a set of discrete points on a plane, the corresponding Delaunay triangulation is generated such that no point sits inside the circumcircle of any triangle. In Figure 4.3, a sail shape reconstructed using Delaunay triangulation theory is shown, we can see that most of the triangles tend to be uniform.

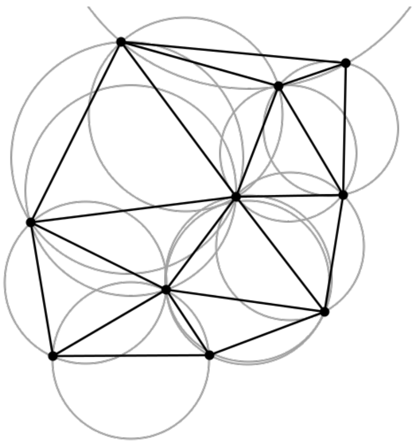


Figure 4.1: A Delaunay triangulation with circumcircles

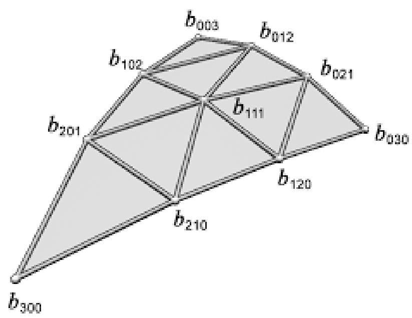


Figure 4.2: The control points of a triangular Bezier patch

However, when we visualize the three-dimensional sail shape based on the Delaunay triangulation reconstruction, the resulting sail shape is coarse and this rough structure introduces artifacts when color-coded.

Therefore, to improve the visual quality of the mesh while preserving the original shape, the curved Point-Normal(PN) triangles algorithm proposed by Vlachos et al. [2001] is implemented, the algorithm refines the visual quality of the triangulation mesh by smoothing out silhouette edges and generating more sample points for shading. Each PN triangle replaces one original flat triangle with an approximation of a curved surface composed of many small (flat) sub triangles. The geometry of a PN triangle is defined as one cubic Bezier patch, the curved patch also matches the deformable and curved nature of the sailcloth. The patch matches the point and normal information at the vertices of the flat triangle.

The geometry of a curved PN triangle is shown in Figure 4.2, where $b_3 00$,$b_0 30$ and $b_0 03$ are the original vertices of the triangle. The remaining points are the control points that are connected to form a control net. The calculation of these control points requires only the position and normal of the input triangle vertices. They are calculated by projecting two vertices into the tangent planes defined by their normal respectively. The center control point is moved from the centroid of the triangle to the average position of all the other six control points until it reaches 1/2 of this distance. In our study, the normal of a triangle is considered as the linear average of the normal of all the neighboring vertices.

In Figure 4.4, the PN triangulation based on the Delaunay triangulation result is shown. We can clearly see that the sail shape mesh becomes much denser and organic when compared to Figure 4.3. When it comes to the visualization of sail shapes, the PN triangle mesh also shows great improvement. It precludes the artifacts introduced by coarse triangulation structure, which is further elaborated in Section 5.2.

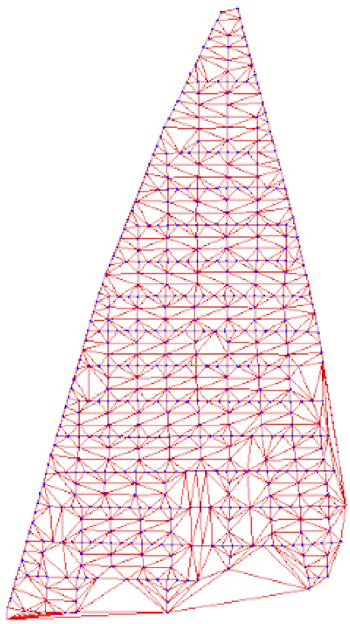


Figure 4.3: Reconstructed sail shape after Delaunay triangulation

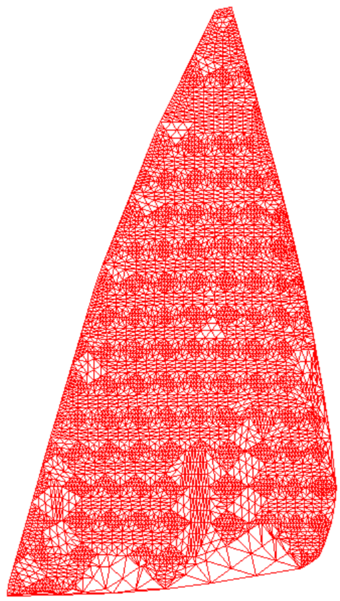


Figure 4.4: Delaunay triangulated sail shape after PN triangle

4.2 CHARACTERISTICS EXTRACTION

The crucial characteristics of sail shape were introduced in Section 2.1 and illustrated in Figure 2.2. In this section, the process of extracting these parameters is presented.

Sail shape characteristics calculation mainly consists of three steps: the adjustment of the point cloud coordinates, sail shape projection and intersection, and the computation of the sail shape parameters.

Coordinate Adjustment aims to rotate and translated the sail shape point cloud so that the plane enclosed by the edges of the sail is aligned to the XOY plane. This adjustment serves for intersecting the sail shape in the second step to obtain the sail profiles. This process contains three steps as listed below. The point cloud after the coordinate adjustment is shown in Figure 4.5.

1. To reorient the sail shape, the normal of the best fitting plane is calculated using Single Value Decomposition. The rotation matrix is then calculated to perform the point cloud rotation from the normal vector of the fitting plane to the normal vector of XOY plane.

2. In order to make sure that the intersections are horizontal, two barcodes which are on the edges of a horizontal line are pre-selected to form the reference line for orientating the sail. The point cloud is rotated around the Z axis by the angle between the reference line and the Y axis.

3. The minimum x,y and z of the point cloud coordinate values are calculated and the point cloud is translated by these offsets in the direction of X axis, Y axis and Z axis respectively.

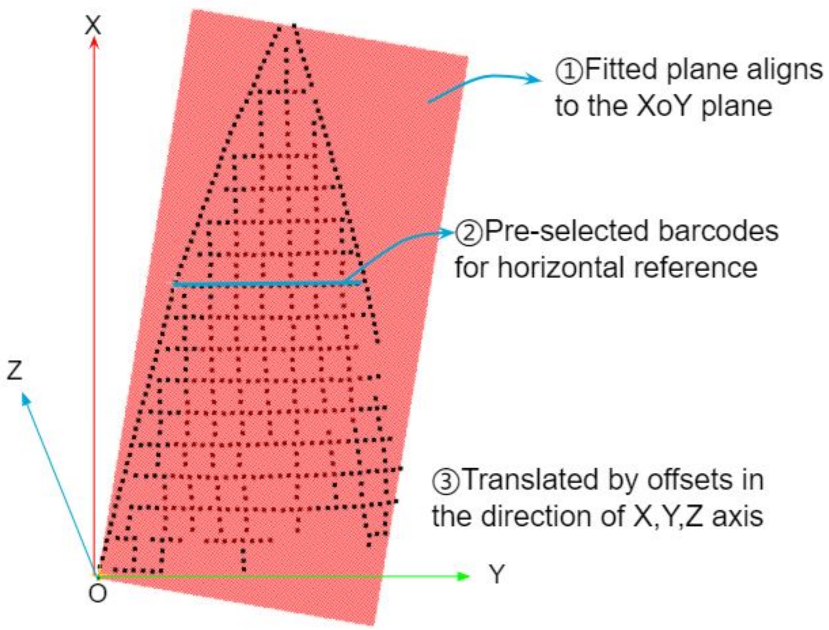


Figure 4.5: Sail shape point cloud after coordinate adjustment process

Projection and Intersection is applied to the sail shape mesh before applying PN triangles remesh algorithm as PN triangles introduce many control points for the sub triangles that might not correspond to the correct sail shape. As the sail shape parameters require more accuracy than the visualization of the three-dimensional shape, the triangulation mesh that is solely reconstructed from the sail shape point cloud is utilized in this step.

In order to acquire the profiles of the sail at a different position, the sail shape mesh is first projected to XOY plane. As shown in Figure4.6, the blue line is the chord line which is parallel to the Y axis, its x coordinate value can range from 10% to 90% (the rest is ignored due to inaccuracy) of the total height of the sail for obtaining the cross-sections at these positions. The orange points are the intersections between the triangle edges and the chord line. Their x and y coordinate values can be calculated directly from the intersection. Their z coordinate value is linearly interpolated from the two endpoints of the triangle edges.

The intersection result is shown in Figure 4.7, the profiles of the sail are on the YOZ plane and the blue points are the intersection between the triangle edges and the chord line.

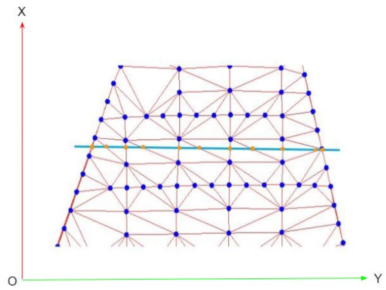


Figure 4.6: Intersection of the sail shape mesh

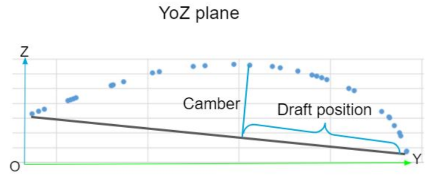


Figure 4.7: Intersected profile of the sail shape mesh

The computation of the sail shape parameters is the last step of the characteristics extraction. The camber and draft position can be easily computed, as illustrated in Figure 4.7. The camber is the maximal distance between the intersected points to the chord line and the draft position is the position of the camber on the chord line in percentage.

There are several definitions of the exit angle and entry angle, in our study, they are defined as the tangent angles of the profile at two ends based on the interviews with the sailing experts. In order to compute the tangent angle of the profile curve, a fourth-degree polynomial is used for fitting the intersected points as shown in Figure 4.8, the red points are the intersected points and the dark blue curve is the fitted polynomial. The entry angle is the angle between the tangent line and chord line at the luff. The exit angle is computed the same way at the leech.

The twist angle in our research is defined as the angle between the tangent line at the leech and the baseline, as shown in Figure 4.9. The baseline is defined as the chord line of the profile at 10% height, as shown in Figure 4.8.

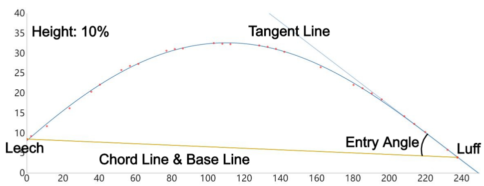


Figure 4.8: Fourth degree polynomial fitting of the profile at 10% height

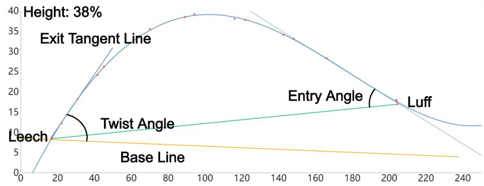


Figure 4.9: Fourth degree polynomial fitting of the profile at 38% height

4.3 PROFILE CURVE FITTING

In Section 4.2, when we compute the exit angle and entry angle from the cross-section of the sail, a fourth-degree polynomial was used for fitting the profile curve. The reason for using polynomial fitting is that we need a general curve to represent the shape of the profile, and to be able to calculate the tangent angles of the profile at both ends. However, in this section we need to visualize the profile for inspection and analysis, and fourth-degree polynomials may not always match the start and endpoint of the profiles. Therefore, we employ another curve fitting method to visualize the profile. In order to control the endpoints of the fitted curve and have a smaller residual, we utilized the piecewise cubic Bézier curve fitting algorithm proposed by Schneider [1990].

This curve fitting method uses cubic Bézier curves as the fitting curve, which were developed by P.Bézier in 1962 (Rushdi [1997]). An example of the cubic Bézier curve is shown in Figure 4.10 (Schneider [1990]), V_i are the control points and a Bézier curve of degree n is defined as:

$$Q(t) = \sum_{i=0}^{n} V_i B_i^n(t), \quad t \in [0,1] \tag{4.1}$$

The $B_i^n(t)$ term in equation 4.1 is the Bernstein polynomial:

$$B_i^n(t) = \binom{n}{i} t^i (1-t)^{n-i}, \quad i = 0, ..., n \tag{4.2}$$

From the derivative of the Bézier curve, as shown in the equation 4.3, we can see that at the left end of the cubic Bézier curve, the line segment from V_0 to V_1 in Figure 4.10 determines the direction of the tangent vector. Note also that V_0 would be the endpoint of another segment when joining many segments together. Therefore, in order to enforce the continuity of the fitted curve at the joints, the third control point of one curve needs to be on the same line with the first and second control points of the adjoining curve. As shown in Figure 4.11(Schneider [1990]), the second control point of the right adjoining curve, denoted as W_1 needs to be on the VW line.

Thus, in order to enforce the continuity of the fitted curve, the second and third control points are placed in the direction of the tangent vector of the first and last control points, respectively. Their positions are calculated by minimizing the error of the fitted curve, that is the sum of the squared distance between the input points and the fitted curves.

The algorithm starts by fitting a single cubic Bézier curve and computing the error between the curve to the input points, if the error is smaller than the error specified by the user, then the algorithm stops. Otherwise, the input points are separated into two subsets at the point of the largest error, the unit tangent vector at the point of splitting is calculated and the algorithm recursively fits new cubic Bézier curves until the error is smaller than a specified error.

The result of the cubic Bézier curve fitting is demonstrated in the profile visualization as shown in Figure 4.11.

$$\frac{d^k}{dt^k} Q(0) = \frac{n!}{(n-k)!} \triangle^k V_0 \tag{4.3}$$

4.4 3D SAIL SHAPE DEFORMATION

As mentioned previously in Section 1.2, due to the uncertain photo quality and the possible obstacles from the sailors, the acquired sail shape point cloud might miss some parts. In order to provide a more complete sail, a template sail is deformed while respecting the known positions of the input point cloud.

The deformation process contains two steps: a rigid transformation of the input point cloud and deformation of the template sail using the input points as constraints. For the first step, the sail shape mesh (Delaunay triangulation) with 96% of the total barcodes are detected is chosen as the template for the first three runs and

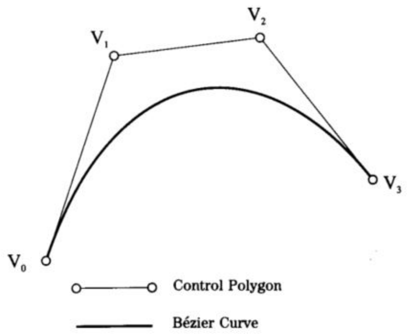


Figure 4.10: An example of cubic Bézier curve

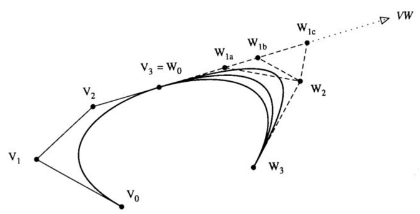


Figure 4.11: Piecewise cubic Bézier curve fitting condition

the template for the last round is a sail shape with 84.5% of the complete barcodes. A rigid transformation is applied to the input point cloud to better align with the template point cloud. The common barcodes in the input point cloud and the template are used for the corresponding points in the rigid transformation. Then the rotation matrix and translation vector that are used for transforming the input point cloud are calculated in the way that the transformed points best approximate the input points in the least squares sense.

For the next step the template is deformed to match the known part of the input shape while completing the missing parts. Instead of deforming the absolute coordinates of the vertices in the template mesh, the Laplacian coordinate of the mesh is deformed. The Laplacian coordinate encodes the difference of a vertex position from the centroid of its neighbor, thus provides an intrinsic representation of the surface mesh, where the reconstruction of global coordinates from this representation always preserve the local geometry as much as possible, given the modeling constraints (Sorkine et al. [2004]).

The input points are used as constraints to fix the absolute positions of some vertices from the template mesh. The quadratic program that needed to be solved for x coordinate(y, z coordinate is solved the same way) is shown in Equation 4.4, where L is the Laplacian matrix of the template mesh, A is a selector matrix to select the vertices whose coordinate are specified, v_x is the resulting x coordinate vector for all vertices, l is the Lagrange multiplier vector, $\overline{\delta}_x$ is the Laplace x coordinates of the template mesh and a_x specifies the x coordinate value for the selected vertices. This quadratic program is deducted from the Quadratic Programming chapter in Nocedal and Wright [2006].

$$\begin{bmatrix} L^T L & -A^T \\ A & 0 \end{bmatrix} \begin{bmatrix} v_x \\ l \end{bmatrix} = \begin{bmatrix} L^T \overline{\delta}_x \\ a_x \end{bmatrix} \tag{4.4}$$

In order the measure the similarity between the deformed sail shape and the original one, five tests are conducted by removing 20 barcodes from the top, bottom, luff, leech part of the original sail and randomly removing 50 barcodes from the original sail. Then we compare the extracted characteristics between the deformed sail and the original sail. For a clear comparison, we calculated the average, maximum and minimum characteristics difference between them as shown in Tables 4.1, 4.2, 4.3, 4.4 and 4.5 for each sail shape parameter respectively. In order to quantify the error, we present the characteristics of every 10% height of the original point could as shown in 4.6.

As we can see from the above-mentioned comparison tables, the difference of the extracted characteristics between the deformed sail and the original sail is very small, indicating by the average difference for each characteristic. So we could confirm that the deformation model preserves the geometric structure of the sail shape and yields a reliable deformed sail shape that can be used as an estimation for the incomplete sail.

Removed Part	Average	Maximum	Minimum
Top	1.71	6.1	0
Bottom	0.71	2.3	0
Luff	4.43	11.4	0
Leech	1.72	3.2	0.1
Random	1.63	3.7	0

Table 4.1: Maximum camber comparison.

Removed Part	Average	Maximum	Minimum
Top	0.15	0.5	0
Bottom	0.22	4.5	0
Luff	0.17	0.4	0
Leech	0.10	0.3	0
Random	0.19	0.5	0

Table 4.2: Draft position comparison.

Removed Part	Average	Maximum	Minimum
Top	0.59	5.77	0
Bottom	0.3	2.54	0
Luff	1.15	2.66	0
Leech	0.32	2.46	0
Random	0.45	2.21	0.01

Table 4.3: Entry angle comparison.

Removed Part	Average	Maximum	Minimum
Top	0.22	1.76	0
Bottom	0.1	0.67	0
Luff	0.35	0.83	0
Leech	0.36	1.01	0
Random	0.42	1.25	0.01

Table 4.4: Exit angle comparison.

Removed Part	Average	Maximum	Minimum
Top	0.36	3.0	0.01
Bottom	0.14	0.67	0
Luff	0.32	0.75	0
Leech	0.43	1.2	0.01
Random	0.62	2	0.07

Table 4.5: Twist angle comparison.

Height	Maximum Camber	Draft Position	Entry Angle	Exit Angle	Twist Angle
10	259.8	42.6	26.11	17.36	-17.36
20	285.2	46	33.37	18.6	-18.71
30	275.2	41.5	37.81	19.25	-19.51
40	247.9	41.9	39.32	18.36	-19.06
50	212.8	43.1	36.51	16.98	-17.69
60	178.5	46.1	36.56	17.55	-18.57
70	143.3	39.1	31.86	17.96	-19.18
80	100.3	36.8	32.79	17.36	-18.31
90	37.5	41.8	29.89	5.15	-6.21

Table 4.6: The characteristics of the original point cloud

5 VISUALIZATION APPROACH

Before we explain our visualization design, we need to clarify our visualization tasks, which are transformed and abstracted from the domain-specific language to a more generic form after understanding our data.

In Section 5.1, we demonstrate the two main tasks for sail shape visualization: visual inspection of the sail shape and comparison between sail shapes and associated performance data and their corresponding sub-tasks.

In this chapter, we present and elaborate on our visualization approaches to fulfill these tasks. The visual inspection of sail shape consists of three parts:

- The exploration of the three-dimensional sail shape, in Section 5.2, we present the visualization design for exploring the 3D sail shape so the sailors can understand its structure.
- The inspection of the two-dimensional sail shape profile, in Section 5.3, we introduce the visualization methods to visualize the sail shape profiles that aim to help athletes identity the features of the sail.
- The analysis of the derived sail shape characteristics, in Section 5.4 we discuss the visualization approaches to visualize the sail shape characteristics and easily spot interesting parts. The characteristics visualization also enables users to see how these characteristics vary along time.
- The analysis of sailing context, in Section 5.5 we illustrate the visualization techniques to present the sailing context of the sail shape.

Finally, in Section 5.6 we explain how these visualization components are related to each other to provide a complete workflow. After introducing the components of the sail shape visualization tool, we illustrate the visualization techniques that we apply to visually compare the sail shapes, supporting sailors to form and test hypotheses about the factors that affect sailing performance in Section 5.7.

5.1 VISUALIZATION TASK

The goals and requirements for the visualization program have been discussed iteratively during multiple interviews with sailing experts from the Sailing Innovation Center [1] in The Hague. By designing the visualization tool markup based on these interviews and iteratively adjusting it based on the feedback from sailing experts, the requirements from the sailing experts became more concrete and the tasks for the visualization also became clearer and more detailed. To be more specific, the two main tasks and their follow-up tasks are listed below:

Main Task 1: Inspect and analyze the sail shape to get a better comprehension of the sail shape under certain sailing conditions.

- Inspect and explore the three dimensional sail shape to have an overview of the sail shape.
- Inspect the characteristics of the sail shape to identify the interesting area on the sail.

1 https://www.sailinginnovationcentre.nl/?lang=en

- Inspect the profile of the sail at different positions to identify the features of the shape.
- Analyze the change of the characteristics at the same position along time to find out their relation with the sailing performance.
- Inspect the sailing context of the corresponding sail shape to identity the sailing conditions.

Main Task 2: Compare sail shapes to find out the characteristics related to sailing performance

- Identify the changes on the three dimensional sail shape when boat speed changes to find out how the sail shape affect sailing performance.
- Detect the variance of the characteristics when boat speed change to discover how these parameters affect sailing performance.
- Compare the profiles at the same positions of different sail shapes to have a more detailed view of the differences.

5.2 3D SAIL SHAPE VISUALIZATION

In this section, we present the visualization design for three-dimensional sail shapes, aiming to improve the comprehension of the complete sail shape in 3D space, as sailors usually reason about the sail shape in 3D space.

5.2.1 Sail Visualization Color-Coding

When sailors look at the sail stripes, one of the most important aspects they consider is their curvatures, which is called camber as shown in Figure 2.2. The sail camber is the feature that controls the generation of force on the sail. It is important for them to understand the distribution of the camber on the sail. With this information they can tell if the trimming is adequate.

In order to present the sail shape with more details and emphasize the camber parameter, we color the sail shape based on the camber value at each mesh vertex to provide a general view of the camber on the sail. The reason that we choose to use the camber value to map colors is to enable sailors to view the camber in a direct and intuitive way, and because the camber directly reflects the sail shape.

Since camber data is quantitative, a sequential colormap called Viridis is used to map the camber to the sail shape. The Viridis colormap is created by Van der Walt and Smith [2015] under the principle of perceptually-uniform and colorblindness friendly. We choose this bluish to yellowish sequence because we want to provide more details in the camber difference and humans are much more sensitive to middle wavelengths of green and yellow than to the outer wavelengths of red and blue Munzner [2014].

The sail shape color-coding result is shown in Figure 5.1, we can clearly see that there are several areas of camber on the sail. The lower-middle part has the largest camber and the outer boundary has a relatively smaller camber, which indicates the lift's central area and position. Referring to the colormap, sailors can also be informed of the strength of the driving force, which is indicated by the value of camber.

In Section 4.1, we mentioned that we applied the PN Triangle approach on the Delaunay triangulation since its coarse structure introduces some artifacts in the visualization. Examples of these artifacts are circled in red in Figure 5.2.

In addition to the PN Triangles, a customized shader is used for addressing the artifacts issues and to display the color of camber properly. Instead of coloring each vertex of the triangle and linearly interpolating these colors to fill the pixels inside, we use a shader to transfer the camber property to each vertex and linearly interpolate the camber for each pixel inside the triangle. Then we render the colored 3D sail shape with only white ambient light to avoid the uneven light reflection on the sail that influences the camber color when the sail is shown on screen. That is also the reason that we choose to realized our own shader than using illumination models like the Phong shading model proposed by Phong [1975]. The resulting sail shape is colored directly based on their camber value and the artifacts disappear, as shown in Figure 5.1.

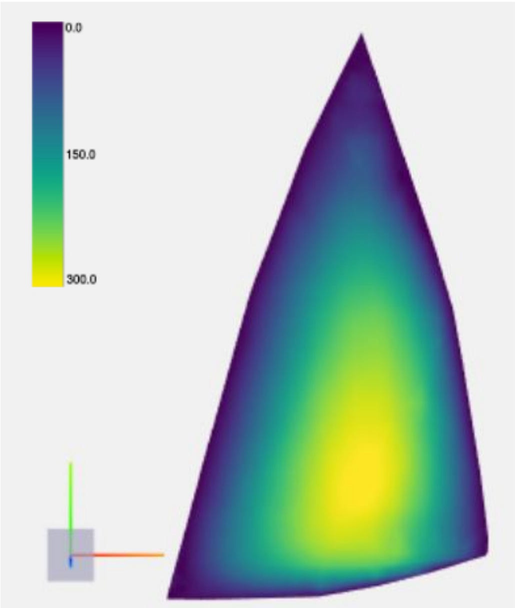


Figure 5.1: Color-coding of PN triangle sail shape

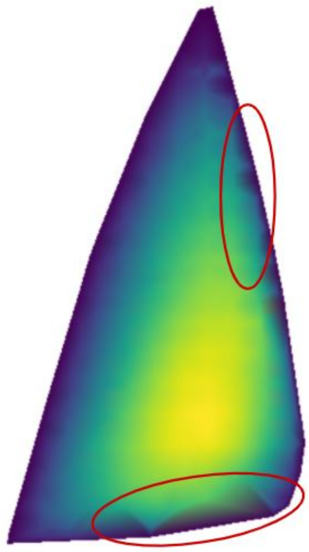


Figure 5.2: Color-coding of Delaunay triangulated sail shape

5.2.2 Sail Shape Contour Line

In order to better perceive the different camber regions, we draw contour lines on the color-coded sail shape, as shown in Figure 5.3. These contour lines represent the area within 50%, 70% and 90% of the 300.0 m camber value, which is the maximal of the colormap. The idea is to facilitate the localization of the lift force of the sail and, therefore, have a better comprehension of the sail structure.

5.2.3 Interactions with Sail Shape

In order to enable sailors to freely explore the sail shape structure, users can rotate, translate, zoom in and zoom out the sail shape on demand, as shown in Figure 5.4. There is a small rectangle on the corner of the canvas with X,Y and Z axis indicator, it moves simultaneously with the sail to demonstrate its orientation so users are less likely to get lost in the exploration.

One characteristic of the multi-hues colormaps is that they generate structure in the visualization, as the visual patterns that are revealed in the visualization are hard to discover in the data. We studied another colormap based on the encoding of the values based on the luminance. So the user can change it as shown in Figure 5.5, by toggling the buttons beneath the sail shape. We choose the sequential blue

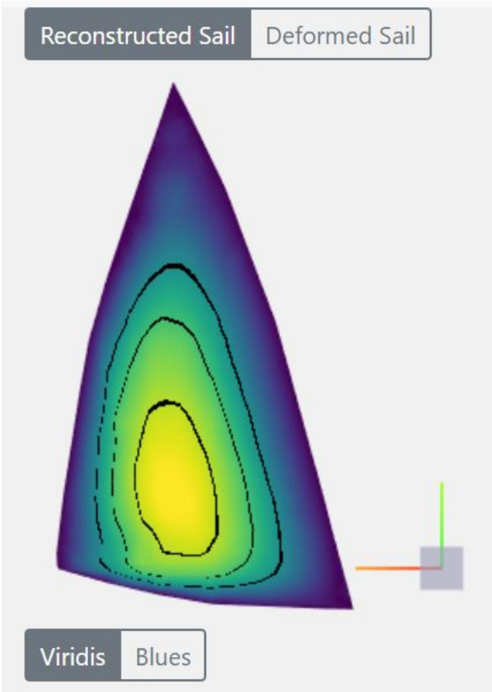


Figure 5.3: Sail shape with contour line

colormap as it is the same used for the camber in the heatmap visualization, present in Section 5.4.

In Section 4.4, we performed five tests to find out how accurate is the deformation model and results indicate that the deformation can preserve the features of the geometric model. Therefore, we include the deformation in the visualization to make it clear which parts were missing and filled by the deformation template.

Users can choose to toggle between the plain reconstruction of the point cloud and the deformed template sail shape. An example is shown in Figure 5.6, the left part of the sail is missing, therefore, resulting in a potentially misleading structure and incorrect characteristics. Figure 5.7 shows the template sail shape deformed version and we can see after filling the right side of the sail, the middle area of the sail forms a larger camber area. These deeper and layered camber areas match the sail shape structure pattern as discussed previously. Moreover, users can use this deformed template to have an estimation of the real sail shape.

5.3 PROFILE VISUALIZATION

By inspecting the full 3D shape, the sailors can explore the camber of the sail, but this visualization does not provide them with all the characteristics of the sail. One way to present a more precise shape of the 3D sail shape model and enable users to access the characteristics of the sail shape is to extract the cross-section of the sail. Moreover, the sailing community is used to explore the sail shape by inspecting the profile of the sail. In this section, we present the approaches to visualize the sail profile. The method that we utilize for constructing the profile curve is discussed in previous Section 4.3.

The goals of profile visualization are to help sailors inspect the sail shape in more detail and identify the relevant features of the shape.

In Figure 5.8, the overall profile visualization is presented. At the top of the figure a table presents the values of all the parameters related to the profile at 43% height of the current sail shape. It allows sailors to inspect the profile quantitatively, it also helps them to compare and record these profile easier.

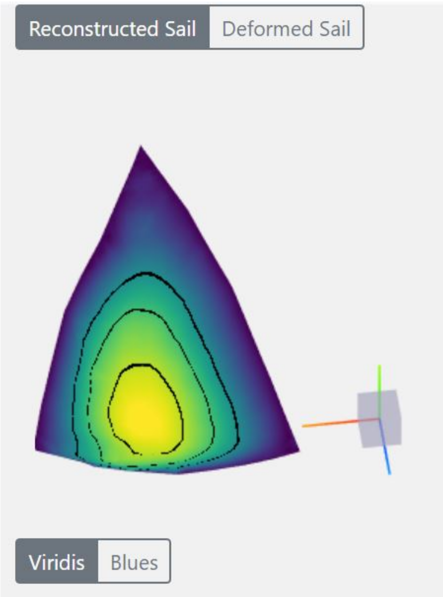


Figure 5.4: Control the sail shape

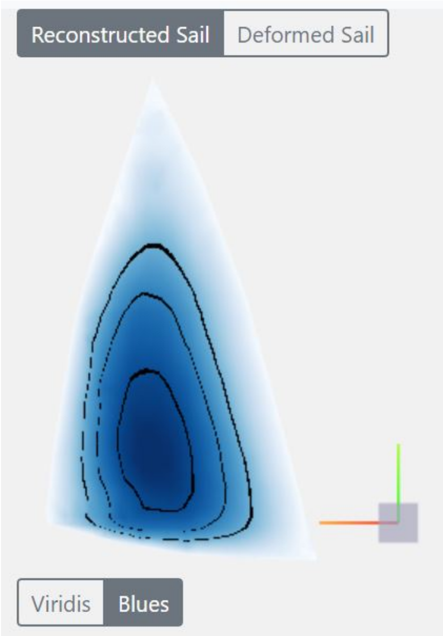


Figure 5.5: Color code the sail shape with sequential blue colormap

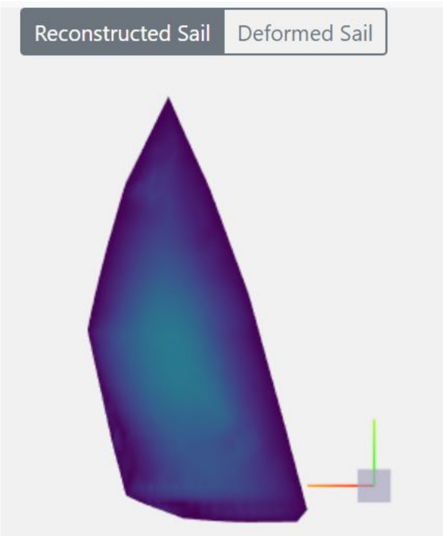


Figure 5.6: Incomplete reconstructed sail shape

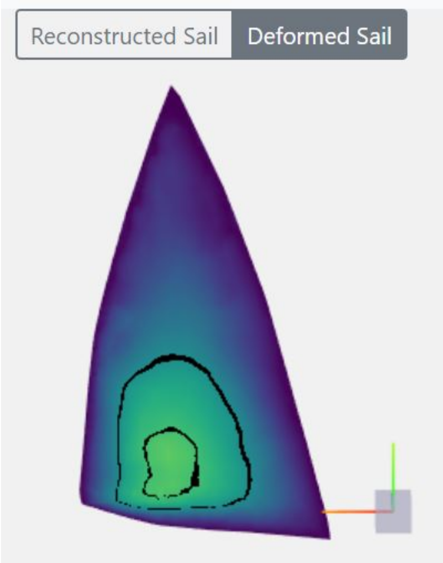


Figure 5.7: Template sail shape deformed by incomplete point cloud

At the middle of the Figure 5.8, there is a plot of the profile. The fitted cubic Bézier curve and the maximal camber line are drawn in blue, the red points are the intersected points from the cross-section as described in Section 4.2. The green line is the chord line and the purple line is the base line of this sail shape (the chord line of the profile at 10% height). There are different ways the users can interact with this profile graph to explore it, which includes drag and drop, zoom in and zoom out, toggle graph overview and reset canvas. By selecting the height slider, the user can also choose the profiles of the sail at different positions, so they can explore the entire sail, this interaction mechanism is illustrated in the following Section 5.6.

At the bottom of Figure 5.8, the user can choose the curve fitting error, so he is able to see the possible wrinkles on the sail shape since the accuracy of the barcodes detection is from 1.0 cm to 1.5 cm. In this Figure, the error is 10.1, so the fitted curves tend to be smooth and not following the points closely. But in Figure 5.9, the error is set to 1.1 and the fitted curves follow the points more closely. By changing the error for the curve fitting algorithm, it is possible to adjust the sail shape according to the sailing conditions to have a more accurate profile curve.

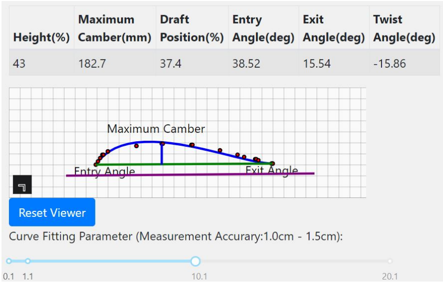


Figure 5.8: Profile visualization overview.

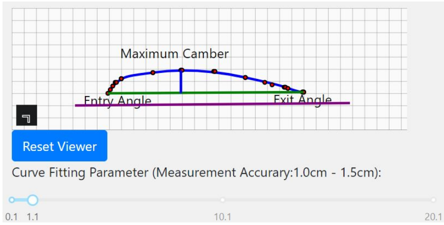


Figure 5.9: Profile curve fitting with different error.

5.4 CHARACTERISTICS VISUALIZATION

In this section, we explain the visualization techniques that are used for visualizing the sail shape characteristics are introduced. These visualization designs aim at helping sailors to spot their interested area on the sail and support the contextualization with other variables.

5.4.1 Characteristics Heatmap

As shown in Figure 5.10, there are five parameters of the sail shape profile that are shown in the characteristics Heatmap, the Y axis indicates the position of the profile. Users can interact with the heatmap by hovering over each rectangle, its corresponding value is shown in a tooltip.

Since maximal camber, draft position, exit angle and entry angle are all quantitative data, sequential colormap are used for coloring their cells based on the value. However, for the twist angle, as it has a diverging range, we use blue-to-red diverging colormap, because the value of twist angle varies from negative to positive and the position where the twist angle becomes positive is interesting to the sailors.

By viewing the characteristics heatmap, users can get an overview of the sail shape and find their interesting area on the sail. In the example shown in Figure 5.10, the maximal camber gets larger at lower sail position, the draft potions has sudden value change at the 85% height, and it could be interesting for users to view the profile shape at that position. The exit angle is more or less the same along the sail but the entry angle also changes significantly at 85% height. Viewing the twist heatmap, we can see that the twist angle becomes positive at 90% height, possibly another interesting position to further analyze the profile.

5.4.2 Speed And Characteristics Analysis

The dual axis chart is chosen to visualize the speed and characteristics analysis chart as shown in Figure 5.11. The left vertical axis shows the value of the selected parameter, which is maximal camber in this case. The right axis indicates the value of speed.

Figure 5.11 it shows the change of maximal camber value (colored in green) and derivative (colored in light purple) along time and the average value (colored in orange) for this time interval. Putting these trends of maximal camber together with

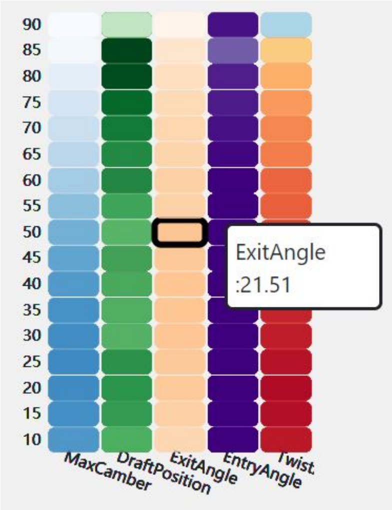


Figure 5.10: Sail shape characteristics Heatmap.

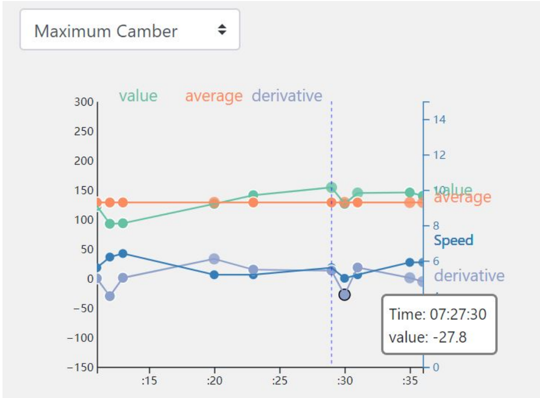


Figure 5.11: Sail shape characteristics analysis chart.

the change of boat speed (colored in dark blue) may be useful to test hypothesis of the relation between maximal camber and sailing speed.

There are several ways users can interact with this chart, users can click on a point to view the sail shape corresponding to this time instance. The dotted vertical line indicates the current time. Users can also deactivate some variables in order to focus on one or a few at a time. As shown in Figure 5.12, only the derivative and the speed are plotted. Except for deactivating some datasets, users could also zoom in to analyze the change of the parameter in a specific period of time. As shown in Figure 5.13, users can choose to visualize the change of all these five characteristics and analyze their relation with boat speed.

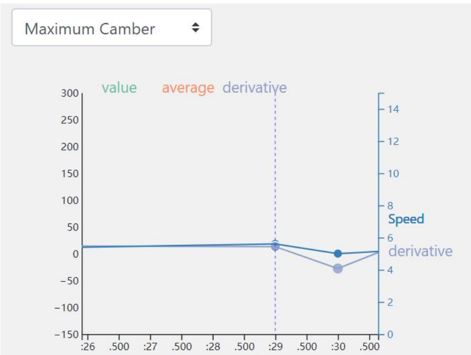


Figure 5.12: Deactivate a trend in sail shape characteristics analysis chart.

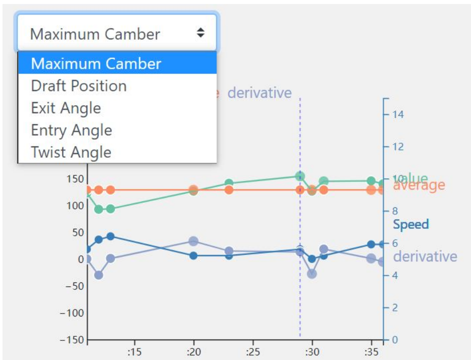


Figure 5.13: Select characteristics in sail shape characteristics analysis chart.

5.5 SAILING CONTEXT VISUALIZATION

In this section, three different methods are applied to visualize the sailing contextualization of the sail shape with the other variables. These approaches include showing the photo of the corresponding sail to indicate the sailing conditions; visualizing the boat speed data of the sail shape to provide information about the sailing performance; visualizing the position of the sail shape in the boat track to help sailors recall the trim setting and the exercise.

5.5.1 Speed Line Chart

The speed line chart is shown in Figure 5.14, the X axis is time and the Y axis is the speed value in Knots units. In addition, this speed line chart also servers as a selection tool to choose a shape from an instant in time. This interaction is further explained in the later Section 5.6.

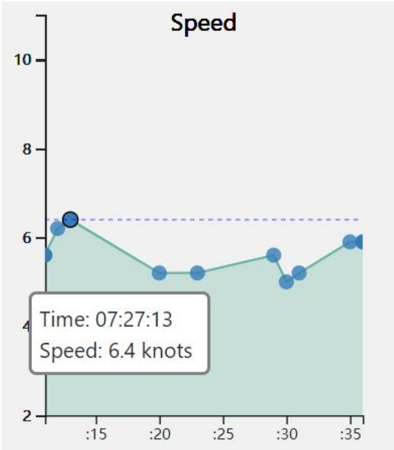


Figure 5.14: Speed line chart.

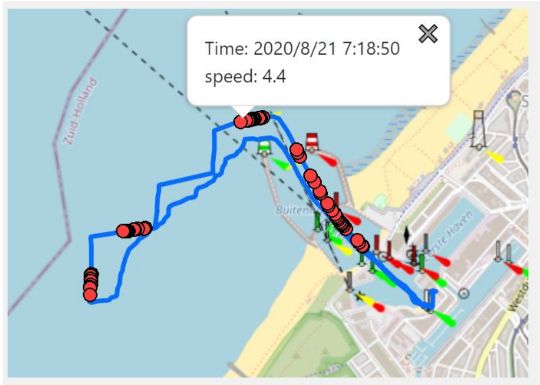


Figure 5.15: Visualizing the boat track on a map.

5.5.2 Sailing Track Visualization

As shown in Figure 5.15, the trajectory of the boat during the whole training session is visualized in blue, the red points means the sail shape at that position is visualized. By interacting with the red points, users can see the time and speed data related to it as well as the sail shape.

5.6 ROUND ANALYSIS OVERVIEW

This section describes how the components described above are placed in the dashboard and are inter-connected. There are two main interactions of round analysis: the selection of profile position and the selection of sail shape.

In Figure 5.16, the slider labeled with 1 is the height selector that controls the height and the corresponding profile characteristics data shown in the characteristics table (number 2) and the position of the profile drawn in the canvas (number 3). By selecting the height via the height selector, users could also change the position of the shown parameter in the characteristics analysis chart (shown in Figure 5.17 in number 4) to analyze the value, deviation and derived of the same characteristics at different sail position along the time axis.

The other main interaction is the selection of the sail shape, which would visualize a different sail shape. Shown in Figure 5.16 by selecting the time instance in the speed line chart (number 5), selecting the position point in the sail track(number 6) and choosing the time in the characteristics chart (shown in Figure 5.17 in number 4), users can select to view the sail shape corresponding to that time instance or position. When a new sail shape is selected, the three dimensional sail shape, characteristics heatmap, profile visualization change correspondingly.

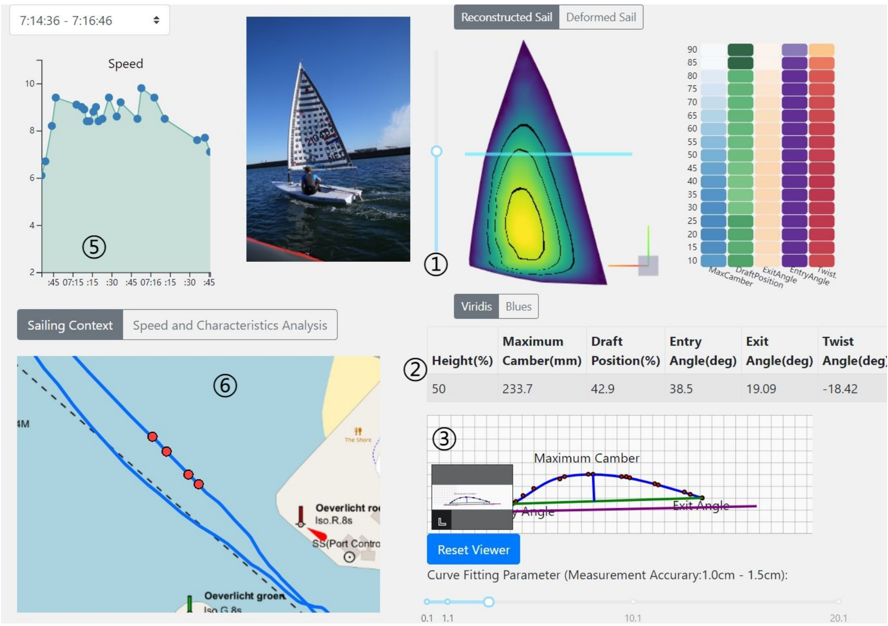


Figure 5.16: Round analysis with sail track.

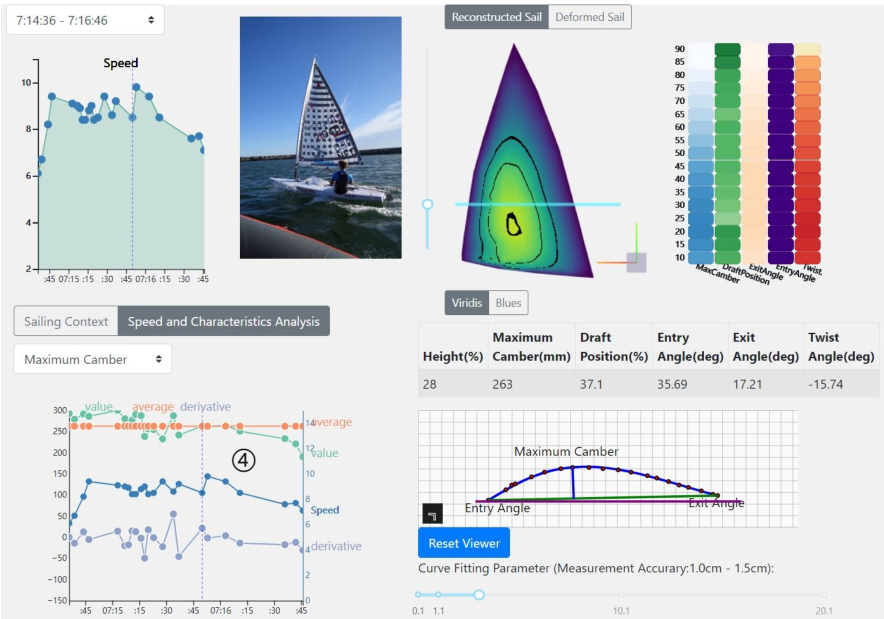


Figure 5.17: Round analysis with characteristics analysis chart.

5.7 SAIL COMPARISON VISUALIZATION

In the section, we explain the visualization techniques that we apply to visually compare the sail shape, which includes the side by side comparison of sail shapes and superimposition of the sail profiles. The goal of the visual comparison is to find out the sail shape that can lead to a better sailing performance by comparing the 3D sail shape, characteristics heatmap and profile of the sail along with its boat speed.

5.7.1 Sail Shape Side by Side Comparison

Separately placing the three-dimensional sail shape, characteristics Heatmap next to each other together with their corresponding speed line chart can help to see the similarity or deviations of these two sail shape and their characteristics easily. We decided to compare the sail shapes by showing them side by side instead of overlaying them because overlaying can result in clustered sails and some parts of the sail structure might be occluded, making it hard to detect the differences.

In Figure 5.18, two sail shapes from the same round with 11 seconds in between, are shown side by side. Because the time difference between these two sails is relatively small, the 3D sail shapes are similar. But we can still detect the change of the sail by viewing the color-coding of the sail and the contour line, the inner contour line area of the left sail is more stretched vertically compared to the one on the right, so we can tell that the area of the main sailing force extended. For a more precise comparison of the sail shape, we can tell the difference of the sail shape in terms of characteristics by comparing the characteristics heatmap. We can clearly see that the entry angle and twist angle of the right sail are generally larger the left one, these differences quantify the variation between these two sail shapes, which cannot be achieved by looking only at the 3D shapes. We also show a comparison example of two sails with different trim setting in Figure 5.19, where the distinction between the two sails becomes more obvious.

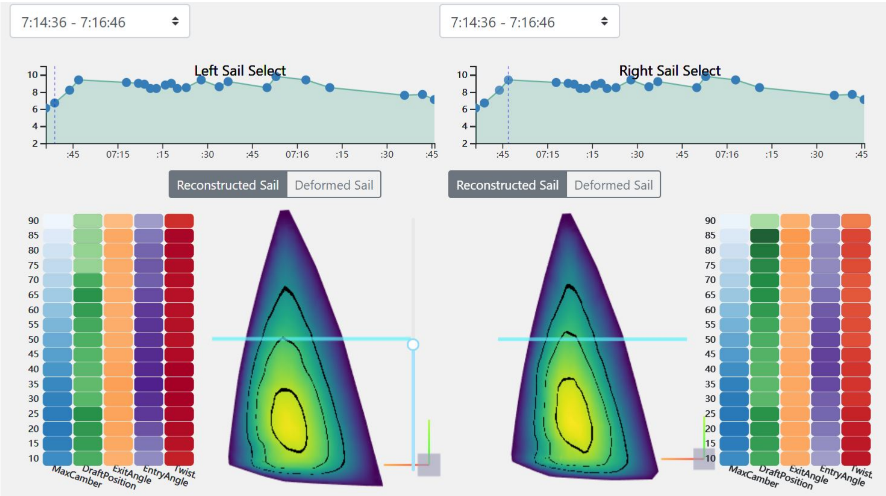


Figure 5.18: Side by side comparison of the sail shape from the same round.

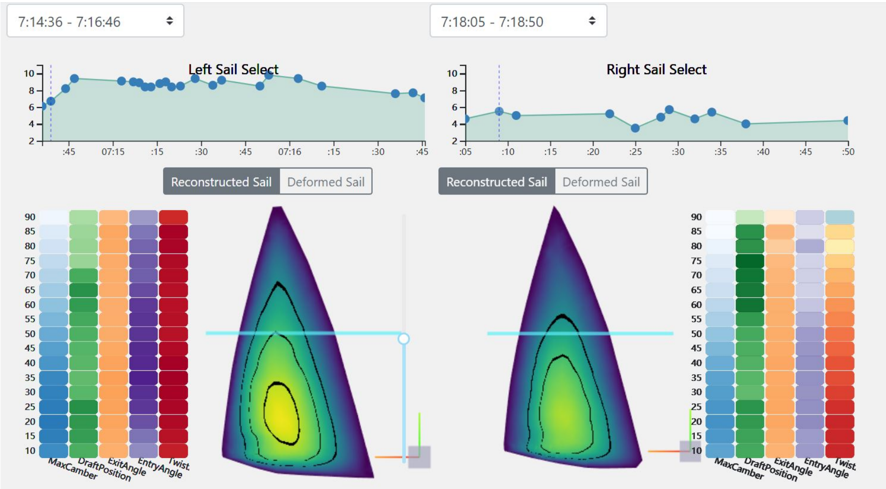
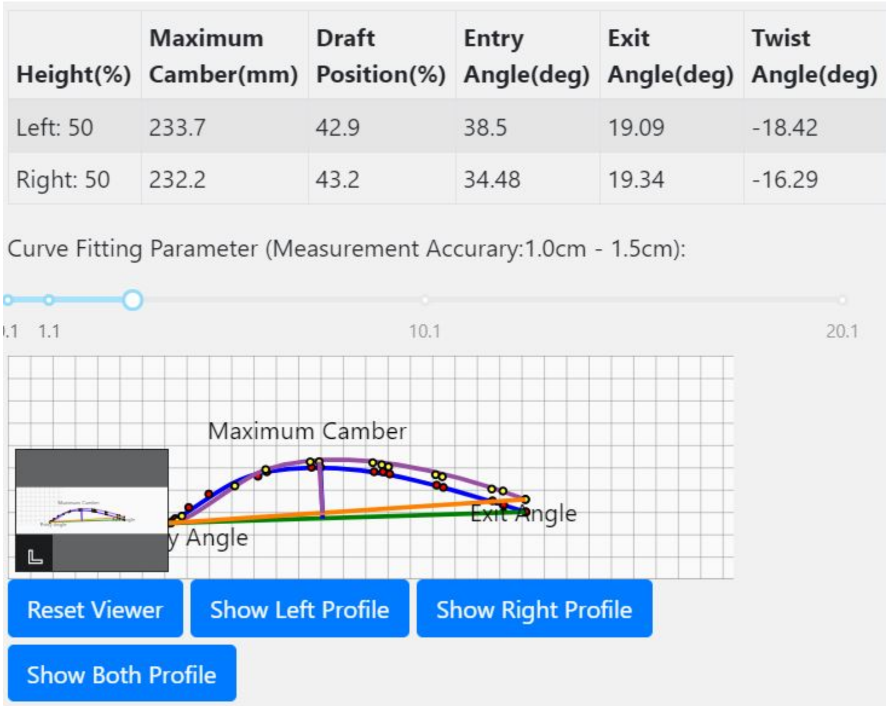


Figure 5.19: Side by side comparison of the sail shape from different rounds.

5.7.2 Profile Overlay Comparison

For the comparison of the profile, we choose to put one profile on top of the other instead of showing them side by side because it is difficult to memorize the exact shape and detail of one profile curve and then compare it with another one. In addition, the side by side comparison cannot indicate slight variations between the two profiles.

Overlaying the profiles better reveals the differences between the profile curve as shown in Figure 5.20. The overlay of profiles is done by matching the left edge of the profile curves and rotating the baseline of the left profile to ensure the two baselines have the same orientation, so the two profiles are at the same position.



Height(%)	Maximum Camber(mm)	Draft Position(%)	Entry Angle(deg)	Exit Angle(deg)	Twist Angle(deg)
Left: 50	233.7	42.9	38.5	19.09	-18.42
Right: 50	232.2	43.2	34.48	19.34	-16.29

Figure 5.20: Superimposition of the sail profiles.

6 EVALUATION

In order to evaluate our visualization and interaction design, and to verify whether it fulfills the tasks of aiding sailors to investigate the relation between sail shape and sailing performance, we need to evaluate the design.

Apart from the interactions during the design process, a qualitative evaluation has been conducted at the end. In Section 6.1, the experiment setting and visualization tasks for the evaluation are introduced and in Section 6.2 we present the evaluation results.

6.1 EVALUATION DESIGN

The test subjects are two sailing experts, one of them is the former World Laser Radial Champion and the other is a sailing expert from the Sailing Innovation Center in The Hague.

The experiments start with the initial introduction of the visualization dashboard and the subjects are required to perform a series of tasks using the visualization tool and answer some questions related to the usability.

The complete tasks and questions are listed below:

1. 3D Sail Shape Evaluation

   Task 1: Inspect and interact with the sailing photo (you are able to drag, zoom in and out the photo).

   - How do you describe the sail shape in the photo?

   Task 2: Explore the 3D sail shape model (you are able to rotate, translate, zoom in and out the 3D sail shape model)

   - Does the 3D sail shape model match your expectation of the sail shape from the sailing photo?
   - How would you describe the sail shape in the 3D model?
   - Do you think the 3D sail shape helps you to have a better perception of the overall sail shape structure?
   - Do you think the color-coding the sail shape with camber helps you to see the curvature of the sail?
   - Do you think the contour lines on the sail shape are useful for understanding the sail shape structure?

2. Characteristics Heatmap Evaluation

   Task 1: Inspect the characteristics heatmap together with the 3D sail shape.

   - Do you think the heatmap helps you to inspect the characteristics of the overall sail shape?
   - Can you find your interested area on the sail based on the heatmap?
   - Would you use it for spotting the point of interest on the sail shape?

3. Profile Visualization Evaluation

   Task 1: Choose the position of the profile using the height slider beside the 3D sail shape and inspect the profile curve and characteristics (you are able to drag, zoom in, and out the profile).

- Does the profile curve match your expectation of the sail shape?
- Does the characteristics of the profile match your impression?
- what details of the sail shape can you see from the profile visualization?

Task 2: Change the curve fitting parameter using the slider below the profile (the parameter decides how close the fitted curve to the points, the smaller the closer).

- Do you think the adjustment function of the profile curve helps you to have a more accurate sail shape based on the sailing context (sailing photo) and measurement accuracy?
- How and when would you adjust the profile curve?

4. Speed and Characteristics Analysis Chart Evaluation

   Task 1: Choose a characteristic of the sail shape that you want to analyze and select the profile position that you would like to inspect using the height slider. **Task 2**: Compare the change of speed and the change of the selected characteristic value and its derivative.

   - Do you think the speed and characteristics chart helps you to find out what characteristics of the sail affect the boat speed and how?

5. Selection Evaluation

   Task 1: Interact with the sailing map and select a sail on the map (single click shows the information of that position and double click shows the sail shape at that position).

   - Do you think the sailing map helps you to select the sail with trimming setting and sailing conditions?

   Task 2: Interact with the speed line chart and select a sail on the speed line chart.

   - Do you think the speed line chart helps you to understand the sailing situation of the selected sail?
   - Does speed line chart help you to select the sail that you want to inspect?

6. Deformation Evaluation

   Task 1: Choose to view the deformed sail shape on the right side, select the same sail using the speed line chart on both sides, and compare the reconstructed sail shape and the deformed sail shape.

   - Do you think the deformed sail shape presents a proper sail shape structure when comparing to the reconstructed sail shape and sailing image?

   Task 2: Choose an incomplete sail (for example, the sail shape at 07:24:31) from the third segment of the speed line chart and compare its reconstructed sail shape and deformed sail shape.

   - Do you think the deformed sail shape presents a proper sail shape structure when comparing to the reconstructed sail shape and sailing image?

7. Comparison Visualization Evaluation

   Task 1: Select the sail on the left side from the second segment (at 07:18:09) and the sail on the right side from the third segment (at 07:25:06), view the reconstructed sail on both sides.

   - In the second segment, the sail is trimmed with a loose setting and the sail has a tight trimming setting in the third segment. Can you describe the difference between these sail shapes?
   - Is the difference of boat speed matching your expectation judging from the wind conditions indicated in the sailing photo?

- What do you think are the factors that cause the difference in boat speed basing on the 3D sail shape and characteristics heatmap?

Task 2: Change the height slider to view the profiles of the sail shape at different positions.

- Can you describe the difference between the profile curves?
- Does the difference match you expectation?
- Based on the visualization, how these differences affect the boat speed?

Task 3: Select left sail (at 07:25:00) and the right sail (at 07:25:06) from the third segment and compare their sail shape.

- They have the same trim setting, but different sail shape and boat speed. Can you describe the difference between these sail shapes?
- How do you explain their difference in boat speed?

Apart from the usability questions listed above, the evaluation ends with these open questions: what would you suggest to improve the sail shape visualization and how do you envision the coaches and athletes using the visualization tool. The open questions point out the direction for future research on sail shape visualization.

6.2 EVALUATION RESULT

The evaluation sessions were done by interviewing with the above-mentioned sailing experts following the testing procedure and enabling them to interact with the visualization tool. During the evaluation, they already gave some advice on the future improvement of the visualization design, these improvement suggestions together with their answers and reaction towards the evaluation tasks are noted. Currently, due to the limitation of accessible data, the sail shape visualization tool cannot fully convey the goal of supporting sailors to discover the optimal sail shape of a given sailing condition. Nevertheless, given the generally positive feedback from the sailing experts, the sail shape visualization has the potential to help the sailors to have a better comprehension of the sail shape in terms of the 3D structure of the sail, the sail profile and the characteristics of the sail shape.

In addition, the comparison and the characteristics analysis enable coaches to form hypothesis about the characteristics and boat speed. In the future, if more information, like wind condition, is accessible and the accuracy of the extracted characteristics of the sail shape is further tested, the sailing experts were positive that the sail shape visualization tool can help sailors to find out the sail shapes that lead to better sailing performance.

We summarize the reaction and answers of the sailing experts towards the visualization tool and we listed the summarization for each visualization component separately below.

1. 3D Sail Shape Visualization

   For the 3D sail shape visualization, we evaluated the quality of the sail shape reconstruction, the visualization design and the sail shape deformation.

   According to both sailing experts, the reconstructed sail shape matches the expectation from the sailing photos and gives the right impression. However, the sailing coach pointed out there was a strange bending on the mast for one time instance, which might be caused by the joint of the sailcloth, barcode detection error or the reconstruction. But generally, the 3D reconstructed sail is a good representation of the sail in the photo in terms of sail depth and shape.

As for the color-coding of the sail, they both agreed that coloring the sail with camber makes it easier to view the depth of the sail and the overall structure. By viewing the contour line together with the color, they mentioned that they could locate the deepest area of the sail and have a more detailed look of this part and where the sail shape is originating. Comparing to the visual inspection of the sail shape, the 3D sail shape with color-coding and contour line helps to quantify the maximal camber area thus provides useful information for fine tuning the boat speed under certain weather conditions.

In addition, the 3D sail shape can be used for training purposes according to the sailing experts. For a beginner sailor, the 3D sail shape can be used to visualize the change of the sail shape when they change the boat configuration, which can be used for explaining the trim process.

When comparing the incomplete reconstructed sail shape with the corresponding deformed sail, they thought that the deformed sail shape is more useful, because if there is a big part of the sail is missing, the incomplete sail shape cannot provide useful information. As for the verification of the deformation model, the sailing experts went through several pairs of the reconstructed sail and deformed sail, they noticed that if the reconstructed sail is almost complete then the two sail are similar, which is considered a correct deformation. But there is also cases that the two sails varied and they could not tell if the deformed sail presents a better representation of the sail shape as both of the sails seems almost complete. They commented that if they could know where are the undetected barcodes, it would increase their confidence in verifying the deformation.

In conclusion, the deformed sail is useful when it comes to incomplete reconstructed sail as it can be used as an estimation of the complete sail and most of the time the deformed sail matches their expectation from the image. But the accuracy of the deformation still needs further research.

2. Characteristics Heatmap

   While exploring the characteristics heatmap, they pointed out that it provides the opportunity to look at the sail shape from a new perspective if they get used to it. Apart from that, they also commented that they could have a more precise look at the exit angle, entry angle and twist angle by viewing the heatmap compared to the 3D sail shape.

   For the usability of the heatmap, the sailing coach said that he would use it to see if the sail shape is consistent and find out where the twist angle change from a negative value to a positive value, in other words, where the sail opens up. To conclude, the heatmap presents a more precise overview of the sail shape from the perspective of the characteristics and it fulfills the task of supporting sailors to spot interesting areas on the sail.

3. Profile Visualization

   The sailing experts gave their approval of the profile as most of the profile curves and the extracted profile characteristics value could match their expectation. They also agreed that the profile visualization enables them to examine the sail shape in more details than the 3D sail shape. However, in some cases the shape of the curve does not exactly correspond to the expectation, but the maximum camber and draft position of the profile still seems correct. They appreciated they can view the profile of the sail from 10% to 90% height of the sail, this gives a lot more information about the sail than viewing only one to three stripes on the sail. The curve fitting adjustment function enables them to adjust the shape of the curve and find out the profile that makes most sense.

4. Speed and Characteristics Analysis Chart

While the 3D sail shape, characteristics heatmap and the profile visualization only show the sail at one time instance, the speed and characteristics analysis chart allow the sailors to inspect the characteristics of sail shape for the whole run. One of the sailing experts commented that if the sail shape characteristics are accurate and they could view the change for a longer period of time with additional information about the weather condition, they could discover how the change of sail shape affects the boat speed.

5. Sail Selection

   The sailing experts thought that all three sail selection functions are meaningful as they allow the sailors to select the sail from a different perspective. They could select the sail that they want to inspect based on speed from the speed line chart or based on sail location from the sailing context map or based on characteristics change from the speed and characteristics analysis. As all the selected components are linked, sailing experts claimed that they could easily understand the context of the current sail shape and select the sail that they want to explore.

6. Comparison Visualization

   When comparing the 3D sail shape side by side, the sailing experts claimed that they could inspect the difference between two sail shapes easily by looking at the color on the sail and the position of the contour line. Displaying the characteristics heatmap besides the 3D sail shape is useful for comparing the characteristics difference between the two sail, the sailing experts commented that by looking at the color applied to the characteristics, they could quantify the sail shape differences. As for the profile comparison, they approved of the overlaying design as they could see the variation between the profiles straightforward.

   One sailing expert commented that it was nice to compare the sail shape with different trim settings along with the boat speed data, it could help to form an initial idea of what trim setting would be more suitable for the given sailing condition. Nevertheless, both experts said that they will need more information about the weather and boat condition to be able to further analyze the sail shape's influence on the sailing performance as in this research we only have the data of boat speed and sail shape point cloud, they cannot draw conclusions on the relation between sail shape and sailing performance because the external conditions can change rapidly. If the wind conditions and boat conditions are acquired and included in this project, they are positive that it is possible to find out the sail shape that corresponds to better sailing performance with this visualization tool.

7. Future improvement During the evaluation, the sailing experts came up with several suggestions to improve the visualization design, which are listed below:

   - In the speed and characteristics analysis chart, the line of the characteristics value can be colored based on the trend of the speed line to help sailors investigate the relation between the sail shape parameter and boat speed. If the speed goes up at the next time instance, we can color the characteristics value point at current moment as blue and if the speed goes down, we color the value point as red. Consequently, the trend of speed is reflected on the characteristics line and it is more convenient for the sailors to link the change of characteristics to the change of boat speed.
   - While inspecting the sail shape, we could show the detected barcodes in some way to indicate the accuracy of the reconstructed sail shape.

7 CONCLUSIONS AND FUTURE WORK

In this research, we aimed at studying how sail shape and sailing performance data can facilitate the trimming process in the intense sailboat competition by supporting the sailors in investigating the optimal sail shape in relation to weather conditions. In order to reach this goal, two main research questions led our work: (1) How to reconstruct the 3D sail shape properly using the point cloud data; (2) What visualization methods are perceived most useful for sailors to analyze the sail shape and sailing performance and enhance their sail shape trimming process.

To achieve a reliable 3D sail shape structure, we first triangulated the sail shape point cloud and then applied a remesh algorithm to obtain a smoother and more organic sail shape. Due to the uncertain image quality and the possible occlusion caused by the sailors when acquiring images, some barcodes cannot be detected thus, the reconstructed sail is incomplete. To tackle this issue, a complete sail shape was selected as the template sail to be deformed under the constraints of the input point cloud.

After recovering the 3D structure of the sail shape, we designed a visualization dashboard for sailors to explore the 3D structure, 2D profiles and characteristics of the time-varying sail shape and analyze their relation to the boat speed. The visualization tool can help sailors to form hypothesis on how sail shape affects boat speed and discover which sail shape can lead to better sailing performance.

During the evaluation interviews with two sailing experts, they confirmed the reconstructed sail shapes matches their expectation after examining the photo of the corresponding sail. They also considered the deformation can be used as a proper estimation of the incomplete reconstructed sail shape. While exploring the visualization dashboard, they commented that it provides an opportunity to look at the sail shape from a new perspective, which has the potential to enhance sailors' comprehension on sail shape and provide insights of the sail shape trimming. Nevertheless, due to the lack of information on the weather condition, sailing experts cannot guarantee the causal relation between sail shape and sailing performance. But they saw this research as the prior work towards a more comprehensive sail shape visual analysis framework and they saw great potential in using this visualization tool for optimal sail shape research.

For future work, there are three interesting directions:

- Retrieval of the average sail shape during a period of time. According to the sailing experts, there are many external factors that influence the sail shape, like wind and waves. These external factors change rapidly, thus instantaneous sail shape might be noise and mislead the analysis of sail shapes over a period. Therefore the implementation of the average sail shape over a certain time interval would help sailors filter out the noisy sail shapes and focus on the more reliable ones.

- In our study, the deformation model is based on the Laplacian coordinate of the template mesh, which yields a reasonable deformation result. Still this deformation applies to generic mesh and does not consider the physics of sail shape. In order to achieve a more reliable sail shape deformation method, the deformation model needs to be based on the physical movement of the flying sail shape. Realizing the sail shape physics model can also reduce the amount of barcodes, they are only needed at the areas where the geometric change are intrinsic.

- As mentioned above and in the evaluation result section, the lack of wind condition and boat data makes it difficult to draw conclusions on the relation between sail shape and sailing performance. So in the future, these data need to be acquired by sensors, and then processed and visualized in the visualization dashboard to fulfill the goal of finding out the optimal sail shape of a given sailing condition.

To conclude, our research proposed a visualization framework for visualizing the sail shape and sailing performance aiming to provide insights into the optimal sail shape in relation to sailing conditions and facilitate sailors' trimming skill. We believe that our visualization design, though having limitations and being preliminary, shows the potential of visual analysis for sail shape and sailing performance.

BIBLIOGRAPHY

Aisch, G. and Quealy, K. (2014). Why peyton manning's record will be hard to beat.

Anderson, B. D. (2008). The physics of sailing. *Physics Today*, 61(2):38.

Aubin, N., Augier, B., Bot, P., Hauville, F., and Floch, R. (2016). Inviscid approach for upwind sails aerodynamics. how far can we go? *Journal of Wind Engineering and Industrial Aerodynamics*, 155:208–215.

Basole, R. C. and Saupe, D. (2016). Sports data visualization [guest editors' introduction]. *IEEE Computer Graphics and Applications*, 36(5):24–26.

Bertin, M. (2015). Why soccer's most popular advanced stat kind of sucks.

Clancy, L. (1975). Aerodynamics (chapter 3). *Topics on pressure fields*, pages 22–59.

Clauss, G. and Heisen, W. (2006). Cfd analysis on the flying shape of modern yacht sails. In *Maritime Transportation and Exploitation of Ocean and Coastal Resources: Proceedings of the 11th International Congress of the International Maritime Association of the Mediterranean, Lisbon, Portugal*, page 87.

Commons, W. (2020). File:delaunay circumcircles vectorial.svg — wikimedia commons, the free media repository. [Online; accessed 3-December-2020].

Delaunay, B. N. (1934). Sur la sphère vide. *Izvestia Akademia Nauk SSSR, Otdelenie Matematicheskii i Estestvennyka Nauk*, 7:793–800.

Deparday, J., Bot, P., Hauville, F., Augier, B., and Rabaud, M. (2016). Full-scale flying shape measurement of offwind yacht sails with photogrammetry. *Ocean Engineering*, 127:135–143.

Freides, D. S. (1991). *An image processing based system for three dimensional sail shape analysis*. PhD thesis, Massachusetts Institute of Technology.

Holle, R. L. (1982). Iv. photogrammetry of thunderstorms. *Thunderstorms–a Social, Scientific, & Technological Documentary: Instruments and techniques for thunderstorm observation and analysis*, 3:77.

Le Pelley, D. and Modral, O. (2008). V-spars: A combined sail and rig shape recognition system using imaging techniques. In *Proc. 3rd High Performance Yacht Design Conference Auckland, New Zealand, Dec*, pages 2–4.

Linder, W. (2009). *Digital photogrammetry*, volume 1. Springer.

Lommers, C. (2015). Descending: Measuring and comparing descending technique and performance in professional road cycling. Master's thesis, Delft University of Technology.

Maciel, L., Marroquim, R., Vieira, M., Ribeiro, K., and Alho, A. (2021). Monocular 3d reconstruction of sail flying shape using passive markers. *Machine Vision and Applications*, 32(1):1–22.

Masuyama, Y., Tahara, Y., Fukasawa, T., and Maeda, N. (2009). Database of sail shapes versus sail performance and validation of numerical calculations for the upwind condition. *Journal of marine science and technology*, 14(2):137–160.

Munzner, T. (2014). *Visualization analysis and design*. CRC press.

Nocedal, J. and Wright, S. (2006). *Numerical optimization*. Springer Science & Business Media.

Phong, B. T. (1975). Illumination for computer generated pictures. *Communications of the ACM*, 18(6):311–317.

Rushdi, A. (1997). Karnaugh map, encyclopaedia of mathematics, supplement volume i, m. hazewinkel.

Sacha, D., Stein, M., Schreck, T., Keim, D. A., Deussen, O., et al. (2014). Feature-driven visual analytics of soccer data. In *2014 IEEE conference on visual analytics science and technology (VAST)*, pages 13–22. IEEE.

Schneider, P. J. (1990). An algorithm for automatically fitting digitized curves. In *Graphics gems*, pages 612–626. Academic Press Professional, Inc.

Sorkine, O., Cohen-Or, D., Lipman, Y., Alexa, M., Rössl, C., and Seidel, H.-P. (2004). Laplacian surface editing. In *Proceedings of the 2004 Eurographics/ACM SIGGRAPH symposium on Geometry processing*, pages 175–184.

Tahara, Y., Masuyama, Y., Fukasawa, T., and Katori, M. (2012). Sail performance analysis of sailing yachts by numerical calculations and experiments. *Fluid Dynamics, Computational Modeling and Applications*, page 91.

Taylor, J., Banks, J., and Turnock, S. (2016). Influence of sailor position and motion on the performance prediction of racing dinghies.

Van der Walt, S. and Smith, N. (2015). mpl colormaps. *SciPy, July*, pages 6–12.

van Hillegersberg, J., Vroling, M., and Smit, F. (2017). Improving decision making in ocean race sailing using sensor data.

Vlachos, A., Peters, J., Boyd, C., and Mitchell, J. L. (2001). Curved pn triangles. In *Proceedings of the 2001 symposium on Interactive 3D graphics*, pages 159–166.

TU Delft