SailVis: Reconstruction and multifaceted visualization of sail shape

Danfeng Mu[1], Marcos Pieras[1], Douwe Broekens[2], and Ricardo Marroquim[1]

[1] Delft University of Technology, Delft, The Netherlands.
[2] Sailing Innovation Center, The Hague, The Netherlands.

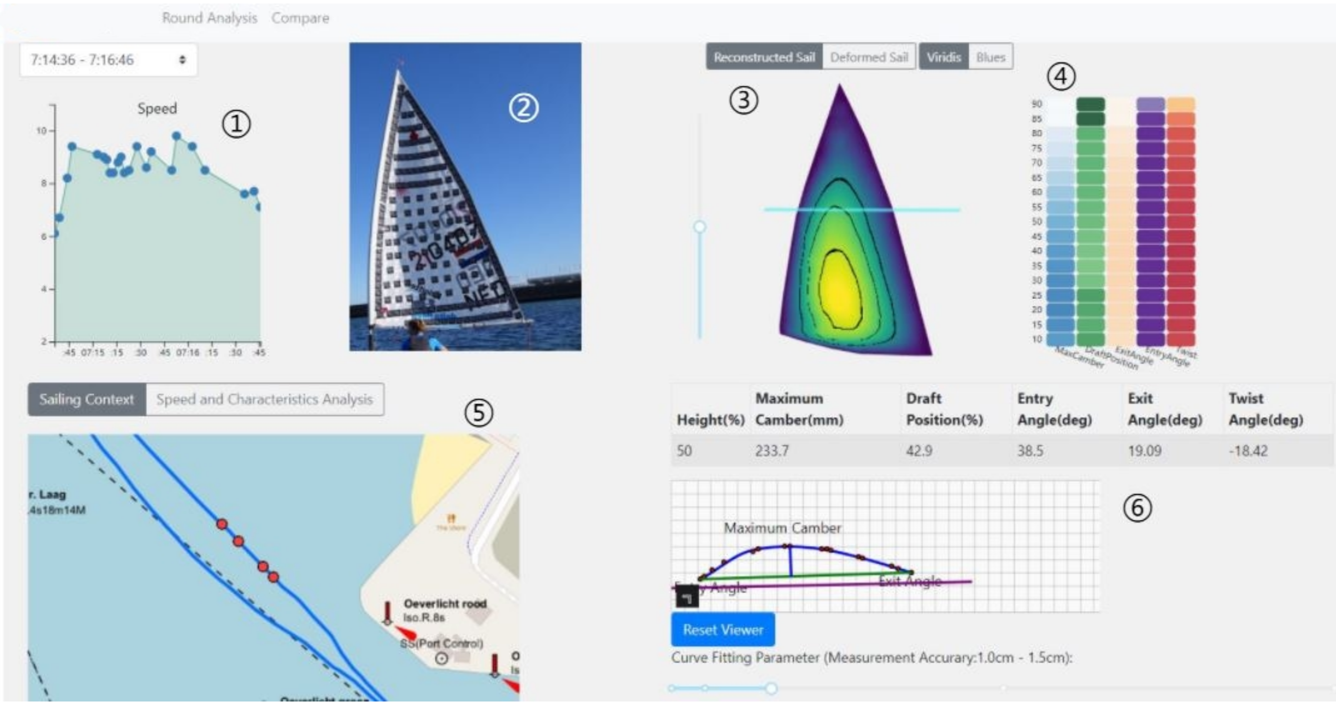

Figure 1: *Initial view of SailVis where the coach can inspect the sail shape at different levels.*

Abstract

While sailing, sailors rely on their eyes to inspect the sail shape and adjust the configurations to achieve an appropriate shape for a certain the weather condition. Mastering this so-called trimming process requires years of experience since the visual inspection of the sail shape suffers from inaccuracies and many times are difficult to communicate verbally. Therefore, this research proposes a visual analysis tool that presents an accurate sail shape representation and supports sailors in investigating the optimal sail shape for certain weather conditions. In order to achieve our goals, we reconstruct the 3D sail shape from point clouds acquired by photogrammetry methods. For incomplete acquisitions we deform a complete template sail to estimate the missing parts. We designed a visualization dashboard for sailors to explore the 3D structure, 2D profiles and characteristics of the time-varying sail shape as well as analyze their relation to boat speed. The usability of the visualization tool is tested through a qualitative evaluation with two sailing experts. The result shows that the reconstruction and deformation of sail shape are plausible. Furthermore, the visualization dashboard has the potential to enhance sailors' comprehension of sail shape and provide insights towards optimal trimming.

CCS Concepts

• ***Human-centered computing*** → ***Information visualization;***

DOI: 10.2312/evs.20211049

1. Introduction

The main driving force of a sailboat is its sail. When set in an appropriate shape, it generates a lift force that makes the boat advance. However, different wind and sea conditions imply different settings to make the boat go faster. Small differences in the sail shape may result in winning or losing a regatta. Hence, it is of high interest to find the optimal relation between the sail shape and weather conditions.

To control the shape of the sail, sailors tighten or loosen ropes attached to different parts of the sail, this process is called *trimming*. Nowadays, sailors rely on their naked eyes to check the sail shape with the help of visual cues, such as painted stripes on the sail. Nevertheless, mastering this visual inspection requires years of training experience, especially since the weather conditions dictate the trimming for achieving higher speeds. For example, under heavy wind conditions, the sail needs to maintain a relatively more consistent and flat curved shape to catch the airflow compared to sailing under light wind conditions.

Independent of the sailor's experience, visual inspection has limited accuracy. Moreover, due to wind changes the sailor might need to adjust the sail shape frequently, making it hard to memorize the shape at different time instances. As a result, it becomes difficult for sailors to communicate the shape to other sailors or coaches as well as to compare shapes under similar wind conditions in order to find the optimal trimming and, consequently, improve performance.

Under this scenario, 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 better *trimming* strategies. Notwithstanding, visualizing the sail shape goes beyond just rendering the 3D point cloud or an extracted 3D surface. In this work we propose to map important characteristics and metrics that might be visualized directly on the 3D sail shape as well as abstract visualizations to aid in understanding the relation of the shape with performance. The main goal is to develop visual strategies for coaching purposes, and our design study contributes in the following ways:

- An interpretable pipeline to reconstruct the sail shape from sensor point cloud data.
- A visualization pipeline to inspect sail shape data at different levels. Mainly:
  - A hierarchical visual inspection of a sail reconstruction.
  - A contextualized comparison approach to contrast sail shape at different time intervals.
  - A contextualization pipeline to compare sail shape with speed performance.

This visualization tool has been iteratively designed in close collaboration with domain experts, namely one sport scientist embedded in a National Sailing federation with 4 years of experience working in technology projects applied to sailing, and a former World Sailing Champion.

In addition, these developments can be used not only for coaching tasks but has the potential to aid in the sail design process, following CFD software and wind tunnel tests [TMFK12].

2. Related Work

To address the issues of visual inspection of sail shape, researches have been conducted to measure and analyse sail shape. There are two main trends of these researches, the first one uses dynamometers to measure the pressure distribution across the sail while measuring the sail shape. Two examples are presented by Clauss and Heisen [CH06] and Masuyama et al. [TMFK12]. The use of dynamometer provides a reliable but sparse reconstruction without the desired detail for sailors.

The second trend is based on photogrammetry by detecting visual cues with high contrast on the sail, such as the sail stripes, and retrieve the curvature along these stripes [LPM08]. However, it requires 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 hold, Deparday et al. [DBH*16] argue 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.

As a variation of the second trend, instead of recognizing and recovering the stripes on the sail, Maciel et al. [MMV*21] attach passive markers on the sailcloth and retrieve a mean sail shape along a time interval for sail design and analysis purposes. Even though they are able to retrieve a complete sail shape, they focus more on the acquisition rather than on the analysis.

The visualization outcome is heavily linked to the acquisition process. Methods that rely on just the visualization of the sparse point cloud generated with the dynamometer do not allow to explore the details of the sail. On the other hand, while photogrammetry methods can achieve denser acquisitions, to the best of our knowledge, the resulting data has not been used to support athletes in improving their *trimming* decisions.

3. Task Analysis

This paper aims to narrow this gap by designing a visualization tool to investigate and analyze the sail shape and sailing performance data as a step towards answering the question: *What is the optimal sail shape given a certain sailing condition?*. In order to answer this question, we take the first steps by reconstructing a reliable sail shape model from the point cloud data and designing an effective visualization dashboard to present the information for sailors to explore and discover which sail shape corresponds to higher boat speed. We define three main goals:

- **G1**: Provide an accurate and interpretable 3D sail shape reconstruction.
- **G2**: Provide a visual design to enable inspection and analysis of the sail shape under certain sailing conditions.
- **G3**: Compare sail shapes to find out the characteristics related to sailing performance.

Our target users are sailing coaches and sailors who want to analyze the acquired data after a training session.

4. Data processing

Capturing and measuring the sail shape is very challenging since it changes continuously due to various external forces. In order to provide an accurate measurement of the sail shape, a photogrammetry rig with two cameras was created. By attaching barcodes to the sail, similarly to Maciel et al. [MMV*21], a 3D point cloud is retrieved. In order to reconstruct a 3D surface from the point cloud, we perform several steps. For the initial reconstruction, Delaunay triangulation is applied as it maximizes the smallest angle in the resulting mesh, avoiding skinny triangles. However, the resulting sail shape is still coarse and introduces artifacts when color-coded for visualization purposes. Therefore, we apply the curved Point-Normal (PN) interpolation algorithm proposed by Vlachos et al. [VPBM01]. It refines the visual quality of the triangulation by smoothing out silhouette edges and generating more sample points for shading.

As aforementioned, the visualization of the 3D shape has limitations. For instance, under perspective projection, angles are not preserved. Therefore, we have to derive important sailing features from the 3D data, such as the draft position, camber and three important angles, as shown in Figure 2. These features are, however, derived from a profile curve of the sail at a certain height. Hence, the cross-section of the sail is extracted by the intersection of a horizontal plane with the sail mesh, generating a set of points on the plane. We then fit a polynomial curve on these points to extract the sail section and compute these features. We repeat this process for every ten percentage height along the sail.

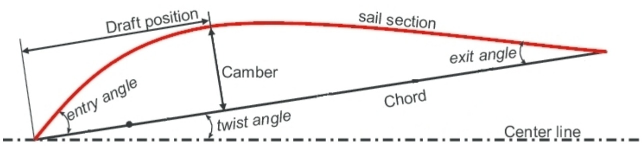

Figure 2: *Cross section diagram of a sail coloured in red with relevant characteristics.*

However, after a couple of onsite trials, we realized that some crucial markers are not retrieved due to strong sun highlights and occlusions caused by the sailors. Consequently, the 3D sail shape contained holes that prevent computing the desired features at all heights. In order to provide a more complete sail mesh, a template sail is deformed while respecting the known positions of the input point cloud following the method from Sorkine et al. [SCOL*04].

5. Visual System

Before explaining our visualization design, we need to extend the visualization tasks that we elicited from a series of interviews with domain experts. We can then list the following subtasks for task **G2** defined in Section 3:

- **G2a**: Inspect the general 3D sail shape as an overview step.
- **G2b**: Inspect the sail characteristics to identify interesting regions on the sail.
- **G2c**: Inspect the profile of the sail shape at different heights to identify the features of the sail.
- **G2d**: Analyze the change of the characteristics along time to find out their relation with the sailing performance.

Furthermore, for task **G3** we define the following subtasks:

- **G3a**: When boat speed changes inspect the changes on the sailing shape.
- **G3b**: Compare the profiles at the same positions of different sail shapes.

Next we will explain the design of each components and how they are linked to follow a complete workflow for the user.

One of the most important aspects sailors consider is the curvature at different heights of the sail. Given a sail profile, the distance from the chord connecting the two end points and a point on the sail is called *camber*, as shown in Figure 2. The camber is the feature that controls the generation of force on the sail. It is important to understand the spatial distribution of the camber on the sail as it gives important clues if a trimming is adequate. We then color code each mesh vertex according to its camber value to provide a general view of the camber on the sail. The reason that we specifically 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 it directly reflects the sail shape. As it is a quantitative value we use the sequential colourmap Viridis. In addition, a set of contour lines is added on the visualized 3D sail shape to distinguish between areas.

The resulting color-coded sail is marked with *3* in Figure 1, and we note that the lower-middle part of the sail has the largest camber while 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.

Next to the 3D visualization, we add its corresponding image (marked as *2* in Figure 1), it helps coaches to get context information of the sail mesh like the state of the sea and the position of the sailor. We also marked the detected barcodes that are used to build the mesh. Based on the number of detected barcodes the user can select whether the sail shape is obtained with the plain reconstruction or the deformed template.

The 3D camber mapping gives a general overview of the sail but does not provide all the detailed characteristics. A more precise way, and that is also commonly used in the sailing domain [Pü18], is to visualize cross-sections of the sail. The goal of the profile visualization is to help sailors inspect the sail shape in more detail and identify the relevant features of the shape. This is carried out by showing the result of intersecting the mesh with a horizontal plane at a given height. By means of a slider it is possible to select specific heights of the mesh to analyze. This idiom is marked with *6* in Figure 1.

As shown in Figure 2, there are five parameters of the sail shape. The profile curve allows users to see sail shape characteristics one height at a time. To allow viewing how these characteristics evolve at different heights we use Heatmaps, where each column represents a variable and each row represents a different height of the sail. Each position is color coded according to the variable that it represents and its quantitative value at that height. For the *Twist angle*, since it has a diverging range, we use a divergence color scheme. Through the Heatmaps, the user can get an accurate overview of the sail shape and find interesting areas on the sail, that can be further explored with the profile encoding. This idiom is marked with *4* in Figure 1.

In addition, using GPS data, we specify the locations where the images were taken on a map. In this way, the sailor can easily relate conditions with locations and training exercises, and select specific sail shapes to inspect. This idiom is marked with *5* in Figure 1.

5.1. G3: Comparison of sail shapes

After inspecting the sail shape, the domain expert expressed the need to compare different sail shapes with performance data like the speed, in order to enable the discussion with which sail configuration leads to a better sailing performance during that day. This is carried out in another tab by rearranging the encodings that previously discussed. Here we juxtapose the 3D sail shapes and the Heatmaps to allow comparison. An explicit encoding or a superposition mechanism would add clutter to the visualization. In contrast, we do superimpose the profile curves since it is difficult to perceive small differences otherwise. In Figure 3 we can see the placement of the location to enable the comparison of sail shapes.

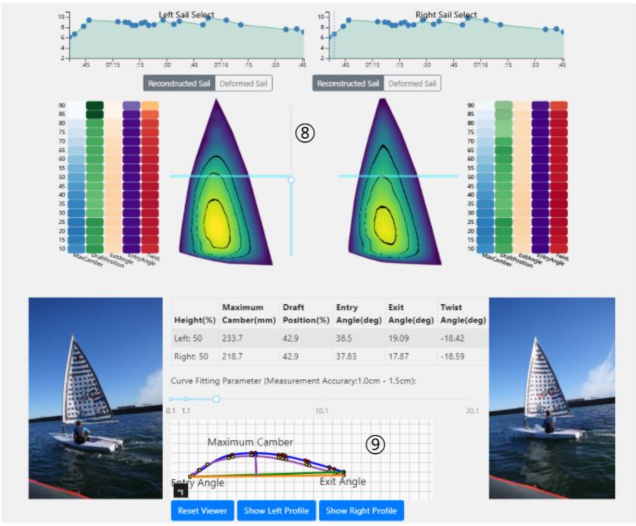

Figure 3: *The Comparison tab allowing to compare two different sail shapes and their details.*

6. Case Study

In order to evaluate the proposed design we tested it with the sailing experts. The evaluation started with an initial walk-through of the dashboard and then we let the experts freely explore the tool. We then had a session with a questionnaire to evaluate the suitability of the tool and to assess some specific points.

For the experts, the reconstructed sail shape matched their expectations. When compared with the photographs, the deformed sail shape provides reliable reconstructions even though some points are missing. The Heatmaps helped to inspect the sail shape but they point out that they need more resolution in some parts to explore how the variables evolve, especially on the *twist angle*, because it is the variable with the largest spatial variation.

After using the tool, they can extract an initial idea of what was the key *trimming* for the run and examine the sail shape in more detail, they are also able to form some preliminary hypothesizes of how it related to the boat speed. For now, the only available data apart from the photogrammetry images was the location and speed extracted form a GPS placed in the boat. However, for a more complete analysis regarding performance more external data is needed, such wind speed and sea condition, as well as trimming information, to make more reliable arguments.

7. Conclusion and Future Work

In this paper, 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 were identified: (1) How to reconstruct the 3D sail shape properly using 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.

During the evaluation process, the domain experts expressed the potential of the tool to enhance sailor's comprehension of sail shape and provide insight into the sail shape trimming process. Nevertheless, due to the lack of information on the weather condition, sailing experts cannot yet guarantee the causal relation between sail shape and sailing performance.

Apart from incorporating such data to improve the analysis, there are several other interesting future directions. For instance, according to the sailing experts, the sail shapes change rapidly. Hence, instead of an instant reconstruction, an average sail shape over a certain time range could be used to avoid the influence of the high-frequency changes.

8. Acknowledgements

This work was supported by the North Sea Innovation Test Area with the help of a financial contribution from the European Regional Development Fund (ERDF). The acquisition rig and photogrammetry process was developed by the project partner Geodelta http:www.geodelta.com. We also would like to thank Ardis Bollweg for providing insight and expertise that appreciably supported the research.

8.1. References

References

[CH06] Clauss G., Heisen W.: 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* (2006), p. 87. 2

[DBH*16] DEPARDAY J., BOT P., HAUVILLE F., AUGIER B., RABAUD M.: Full-scale flying shape measurement of offwind yacht sails with photogrammetry. *Ocean Engineering 127* (2016), 135–143. 2

[LPM08] LE PELLEY D., MODRAL O.: 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* (2008), pp. 2–4. 2

[MMV*21] MACIEL L., MARROQUIM R., VIEIRA M., RIBEIRO K., ALHO A.: Monocular 3d reconstruction of sail flying shape using passive markers. *Machine Vision and Applications 32*, 1 (2021), 1–22. 2, 3

[Pü18] PÜSCHL W.: High-speed sailing. *European Journal of Physics 39*, 4 (may 2018), 044002. URL: https://doi.org/10.1088/1361-6404/aab982, doi:10.1088/1361-6404/aab982. 3

[SCOL*04] SORKINE O., COHEN-OR D., LIPMAN Y., ALEXA M., RÖSSL C., SEIDEL H.-P.: Laplacian surface editing. In *Proceedings of the 2004 Eurographics/ACM SIGGRAPH symposium on Geometry processing* (2004), pp. 175–184. 3

[TMFK12] TAHARA Y., MASUYAMA Y., FUKASAWA T., KATORI M.: Sail performance analysis of sailing yachts by numerical calculations and experiments. *Fluid Dynamics, Computational Modeling and Applications* (2012), 91. 2

[VPBM01] VLACHOS A., PETERS J., BOYD C., MITCHELL J. L.: Curved pn triangles. In *Proceedings of the 2001 symposium on Interactive 3D graphics* (2001), pp. 159–166. 3