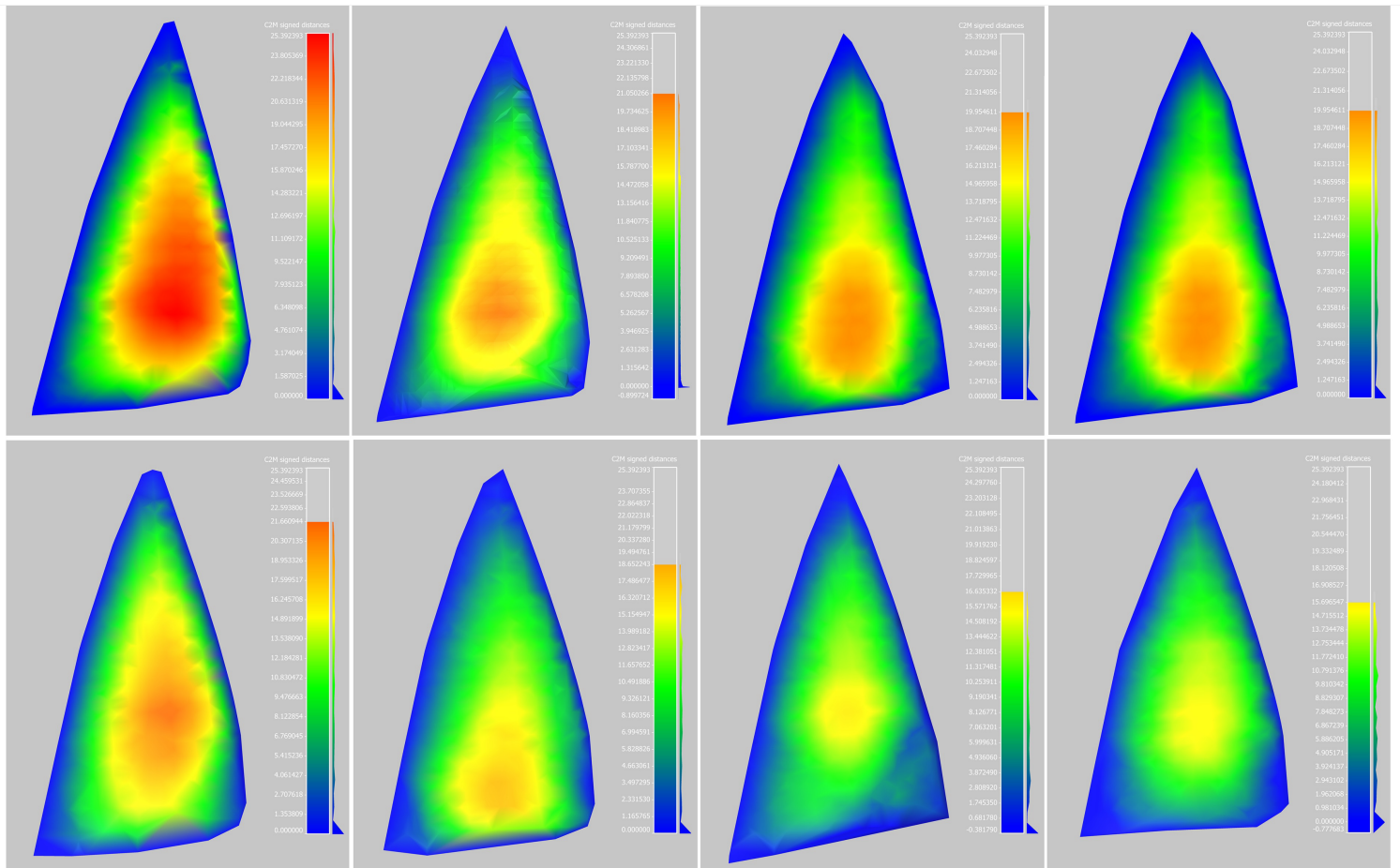




Photogrammetry for yachting

3D flying sail shape techniques

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Project Zero

Version 1.0

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1 Introduction

1.1 Background

In 2019 and 2020, Geodelta pioneered a method to measure real-time 3D sail shapes on a Laser Olympic dinghy. The project, 'Digital Telltales'¹, aimed to capture the 3D sail shape under varying operational ('flying') conditions using photogrammetry. Building on this work, Foundation Zero is interested in exploring whether similar or alternative methods could be applied to Project Zero.

Project Zero aims to be the first large sailing yacht to operate without use of fossil fuels. It will be fully electric, and to generate the energy needed to cover daily operation loads, it will make use of a hydrogeneration system that produces energy by sailing. The energy that can be harvested by hydrogeneration is a function of the sailing speed cubed, which means that a 10% increase in sailing speed may lead to a 33% increase in energy generated. This makes the sailing speed, and thus optimal sail trim, essential to efficient operation of the yacht.

Advanced observational techniques may be a valuable tool in optimizing sail trim. Such techniques can capture the full 3D shape of the sail, which could subsequently be analysed by crew or a computer and combined with data on the boat's performance and conditions to infer actions necessary to optimise the trim. This report investigates the feasibility of different techniques for detecting sail shapes on a large sailing yacht. The main objective is to produce a conceptual design for creating a 3D point cloud of a yacht's flying sails.

1.2 Scope

This report investigates the feasibility of using photogrammetry, as demonstrated in the Digital Telltales project, and other technologies such as laser scanning, to achieve a 3D point cloud to optimal sail trim on Zero. Note that this study does not cover the processing of sail shape data to optimise sail trim adjustment or route optimization.

1.3 Structure

The first section discusses two potential techniques for generating a 3D point cloud: photogrammetry and LiDAR. The next section discusses their application to measuring flying sail shape and explores other methods for sail trim measurement. The last section compares the different methods. Additional background on the Digital Telltales project is provided in the annex.

¹ Eindrapportage Digital Telltales, MKB stimuleringsregeling "Proeftuin op de Noordzee"; A. Bollweg and M. Kodde; 30 april 2020

2 3D measurement techniques

2.1 Introduction

Photogrammetry and LiDAR are two advanced measurement systems that are typically used for capturing the precise geometry of the earth's surface or objects on it. Photogrammetry relies on capturing multiple images of the same object from different angles and using these to reconstruct a 3D model. This technique depends on the accurate alignment of photos and sophisticated algorithms to produce detailed 3D models, making it highly accessible and cost-effective. On the other hand, LiDAR (Light Detection and Ranging) uses laser pulses to measure distances by computing the time it takes for the light to arrive back at the sensor after reflecting from the target object. This provides highly accurate, dense 3D point clouds, even in challenging conditions such as low light or fast movements. Both methods have their advantages: in photogrammetry, individual points can be precisely detected and positioned, whereas LiDAR provides a dense distribution of points on the object. Photogrammetry requires daylight and favourable weather conditions, while LiDAR is less affected by environmental factors. Both technologies have the potential to provide essential insights for designers and engineers in the field of aerodynamics and sailing, enabling them to analyse sail shape with high accuracy and efficiency.

2.2 Photogrammetry

2.2.1 Principles of photogrammetry

Photogrammetry is a technique used to extract data about the shape, size, and spatial position of objects from images. From such data parameters such as distances and coordinates can be inferred, allowing for the creation of accurate 3D models and maps.

A key characteristic of photogrammetry is its non-contact nature, meaning that measurements are taken directly from images without physically interacting with the object. One of the most well-known applications of this method is aerial photogrammetry, see Figure 1.

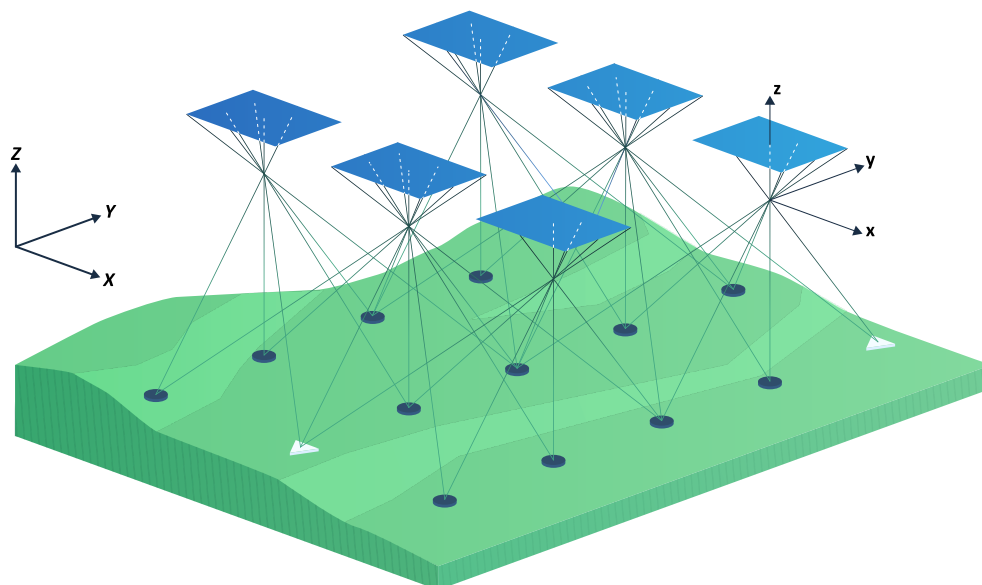


Figure 1 – Principle of aerial photogrammetry. Objects on earth are identified in different images, acquired from various geometries. Their differences in position within the image is used to compute their 3D position.

Photogrammetry is used to derive highly detailed 3D data from overlapping 2D images of a stereo pair. This is done by identifying points representing the same feature in each image of the stereo pair (either by hand or using computer software). From these points, the 3D coordinate of the feature can be determined. A feature is a for the software recognisable point in the image. With stereoscopic measurement the observation of the feature in two images can be computed to a 3D (X,Y,Z) -coordinate (see point (x_1,y_1) and point (x_2,y_2) in Figure 2).

With multiple overlapping images (as in Figure 1), points from each image are used to reconstruct the (X,Y,Z) -coordinate of a feature more precisely. Hence, the presence of a feature in more than two images increases the quality of the whole photogrammetric block.

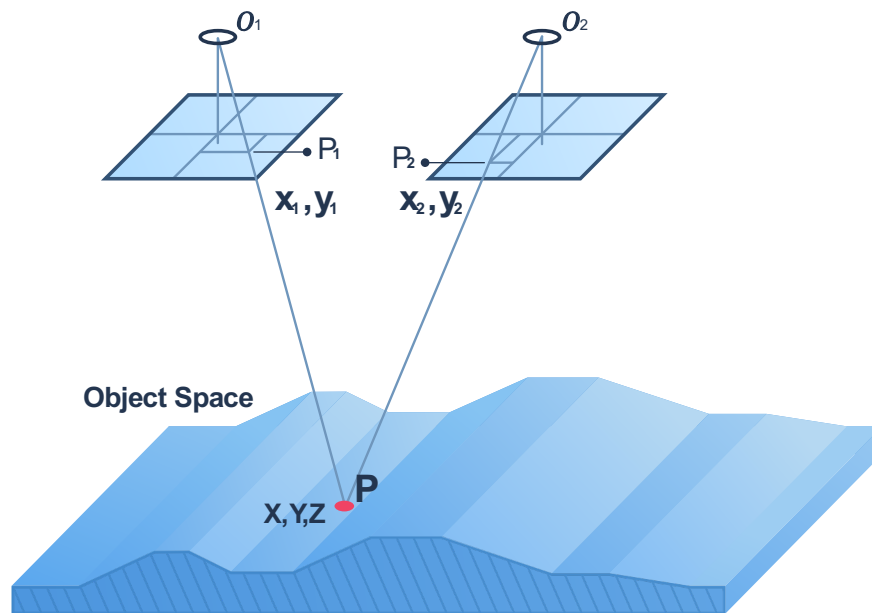


Figure 2 - With photogrammetry the 2D position of a point in two images is used to compute the 3D position of that point on the surface.

Control Points

Photogrammetry relies on the introduction of a reference system, orientation, and scale to the solution. This is done by using Control Points (CP), which are known points in 3D coordinates in a reference system. This reference system can be a national reference coordinate system (such as RD for the Netherlands) or a local reference system. The Control Points are marked and are identifiable in the images. In aerial photogrammetry these points are typically painted circles on a flat area, whereas in local photogrammetry these points can be markers or circular barcodes. These Control Points are essential for transforming 2D images into an accurate 3D dataset.

Camera parameters

To be able to process the images with the photogrammetric workflow, some essential camera parameters must be known. The following parameters are needed:

- Image size (horizontal and vertical in mm or pixels)
- Pixel size (in μm)
- Focal Length (of a fixed, i.e. no-zoom lens)
- Principal point (in mm)
- Lens distortion

The first two parameters are known from the specifications of the camera. The other three parameters must be obtained by calibrating the camera. The focal length of a camera lens is the distance between the optical centre of the lens and the image sensor when the lens is focused on a subject. Figure 3 shows the principle of photogrammetry schematically. When image size, pixel size and focal length are known, the object distance can be calculated. When using two or more images, the 3D coordinate of the target object can be computed.

The *principal point* of a camera refers to the point on the image sensor where the optical axis of the lens intersects the sensor plane. It is the center point of the image where light rays passing through the camera lens converge. Ideally, this point should be at the exact centre of the image sensor, but due to slight misalignments in manufacturing, it might be offset slightly. The principal point is important, as it affects how images are geometrically interpreted and how accurately a 3D reconstruction can be derived from 2D images.

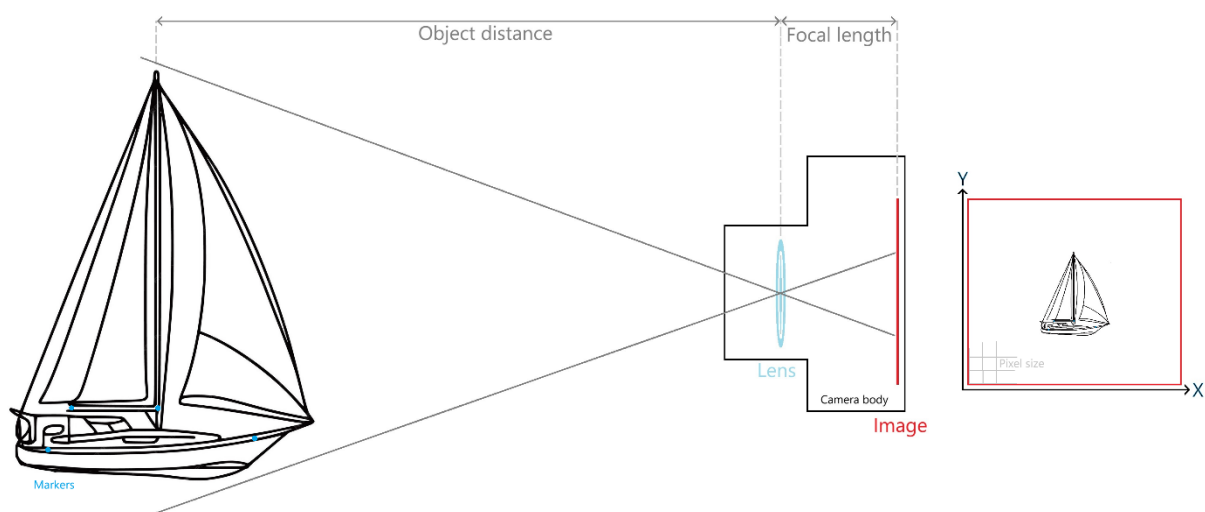


Figure 3 - The principle of a fixed focal length, sensor and pixel size each pixel in the image.

Lens distortion is a common optical effect in cameras that causes straight lines in the real world to appear curved or distorted in the captured image due to imperfections and design of the camera lens.

To calibrate a camera, multiple images have to be taken of a scale bar or calibration room with known Control Points. Figure 4 shows a 3D scalebar with accurate known Control Points, in this case circular barcodes. The coordinates of this scalebar barcodes are known. In all the images the Control Points are automatically detected. Every barcode detection in an image is an observation. By using all these observations and Control Points, the position and location of all the images can be calculated, including the focal length, principal point and lens distortion parameters.



Figure 4 - Control Points Scale Bar to calibrate a camera.

Image triangulation software

For the calibration as well as for the photogrammetry, triangulation software is used. The input needed is (i) all images, (ii) the camera parameters and (iii) the known Control Points. Subsequently the triangulation software executes the following steps:

1. Detect the known Control Points automatically (using the circular barcodes or other automatic detectable markers)
2. Determine the observations of the Control Points in the image reference system
3. Find corresponding features in each overlapping pair of images, for instance using tools such as SIFT or Superglue. Figure 5 shows an example of corresponding features.
4. Determine these observations in the image reference system using the internal camera parameters
5. Group all features representing the same point over multiple images to create tie points.
6. Calculate an approximate position of the 3D coordinate for each tie point.
7. Create a connected system of images, tie points and Control Points (Figure 1).
8. Adjust the positions of 3D coordinates of the tie points and the positions and rotations of the images, such that the whole system fits together.
9. Use the adjusted positions and rotations to generate an accurate 3D model of the object/surface.

Software that executes these steps is available in a number of open-source solutions. One notable example is COLMAP [source: <https://colmap.github.io>], which contains an implementation for the entire pipeline. A number of modifications might be necessary to adapt COLMAP for use in the specific application of sail shape detection, for example for dealing with fixed camera positions.



Figure 5 - Finding corresponding features in each overlapping pair of images. These points are called tie points.

2.2.2 Application in a close-range context

When photogrammetry is applied from the ground, it is referred to as ground-based or close-range photogrammetry. In contrast to aerial surveys, smaller and more affordable cameras can be used, e.g. mounted on drones or tripods. Close-range photogrammetry provides an efficient and flexible way to capture highly accurate 3D spatial data for smaller or more confined areas. The principle of stereoscopic measurements with overlapping images remains the same as in aerial photogrammetry. Control Points, such as circular barcodes or physical scales, are used to enhance accuracy. Additionally, the reference system can either be a local 3D coordinate system or a national reference system, depending on the project. In Figure 6, a systematic layout of a close-range photogrammetry project of Dutch canal houses is shown.

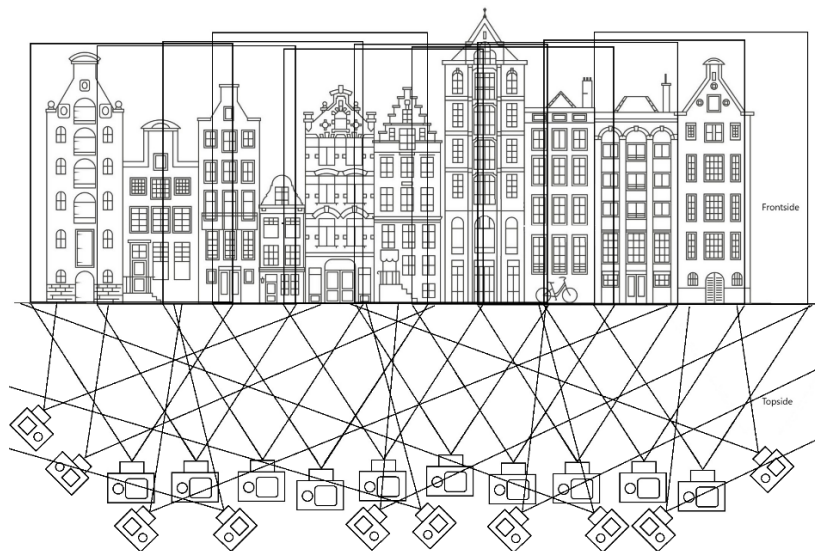


Figure 6 - Close-range photogrammetry. Overlapping images with different positions and orientations to measure buildings.

The following restrictions should be considered when using close-range photogrammetry:

- The object-to-camera distance is limited, from millimeter up to approximately 300 meters
- The camera should be calibrated and used with a fixed focal length
- A scale is established using known points (Control Points)
- The overlap of all the images is covering the entire target object

2.2.3 Static vs dynamic photogrammetry

Traditionally photogrammetry requires multiple images from different locations and orientation of a *static* target object. This is usually achieved by using a single camera and making images over a time period.

In the application of detecting a sail on a large yacht, the target object is deforming and therefore the traditional photogrammetric procedure needs to be adjusted. Instead of using a single camera in multiple positions, multiple cameras can be used that take images from different position at the same time. In this case, the photogrammetric principle still applies. When the cameras are fixed and the position and orientation of all cameras are known in a local coordinate system, the transformation from image reference system to local coordinate system can be computed. This can be achieved by introducing a scale using Control Points (these can be for example markers or barcodes). The time synchronization of the cameras is a mandatory condition when using photogrammetry for *dynamic* target objects.

2.3 LiDAR

2.3.1 Principles of LiDAR

LiDAR (Light Detection And Ranging) is a remote sensing technology that uses laser pulses to measure distances by calculating the time it takes for the light to travel to the target object and back. LiDAR generates precise, high-resolution 3D models or "point clouds" by emitting millions of laser pulses per second and measuring their return times. Long range LiDAR systems are highly effective for mapping terrain, structures, and natural environments, even in low-light conditions or through obstacles like vegetation.

Short-range LiDAR systems, typically with ranges under 100 meters, are used in various fields for applications where high precision over a limited distance is essential. Examples include autonomous vehicles, industrial automation, robotics, navigation, augmented and virtual reality, 3D scanning and medical applications.

Principle of LiDAR

LiDAR operates by emitting a series of ultrashort laser pulses that reflect off a target object. An optical sensor detects the returning pulses, and the distance is precisely calculated by measuring the time it takes for each pulse to travel to the object and back. One pulse measures the distance to one single point. The horizontal distribution of points varies by the way the laser pulses are emitted (rotating or directional). The vertical distribution of points is determined by the number of lasers stacked on top of each other, referred to as channels.

These resulting points form a point cloud. The density of the point cloud depends on the distance to the object and the scanning frequency. The further away the object is, the lower the resolution.

Scanning method: rotating or directional

There are two kinds of LiDAR sensors: rotational and directional. They differ in their scanning methods and field of view. In both scanners parts are moving. In rotational scanners, the lasers rotate 360 degrees, leading to a 360 degree field of view horizontally. These scanners are in general a bit bigger and may consume some more power in comparison to the directional scanners. In the directional scanners, other parts are moving, not the laser sensors. Therefore these systems are generally more compact. They are typically more energy-efficient and easier to integrate into compact designs. The horizontal field of view is limited.

Channel distribution

The vertical field of view is determined by the number (varying from 16 up to 128) of laser pulses (called the channels) and ranges from 22,5 to 180 degrees. The distribution of the laser pulses can be uniform or gradient over the vertical field of view, leading to a uniform resolution or a higher resolution in the middle of the field, respectively (see Figure 7). The gradient distribution is mainly developed for applications in the car industry.

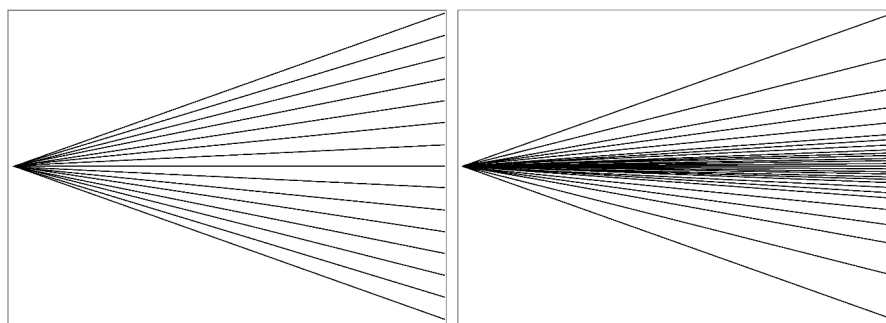


Figure 7 – Simplified illustration of vertical distribution: uniform (left) versus gradient (right) distribution of the channels.

Range

The range of a short range LiDAR system varies from 0,5 to 200 m with a 10% reflectivity range. The term "10% reflectivity" refers to the ability of the sensor to detect objects or surfaces that reflect only 10% of the laser pulse's energy. If a LiDAR system has a specified range of 100 meters at 10%

reflectivity, even for low-reflectivity objects like dark surfaces can be reliably detected up to 100 meters away. For highly reflective objects, the range could be even longer.

Accuracy and precision

In general, the quality of a LiDAR sensor can be described in terms of accuracy and precision, see also Figure 8. Accuracy refers to how close a measurement is to the true or accepted value. It reflects the correctness of the measurement. High accuracy means that the measurements are very close to the actual or standard value. Precision, on the other hand, describes the consistency or repeatability of measurements. It indicates how close the measurements are to each other, regardless of whether they are close to the true value. High precision means that repeated measurements yield similar results, even if they are far from the true value.

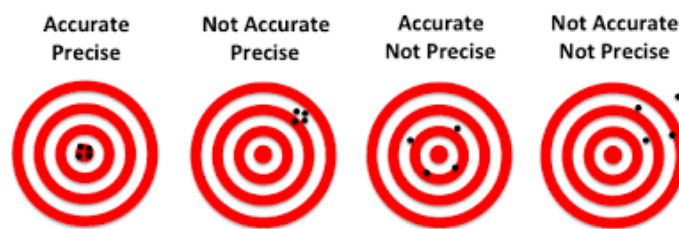


Figure 8 - Accuracy and precision

For LiDAR the quality can be split in the range accuracy and angular accuracy. The distance accuracy varies from 0,5 cm to 5 cm. The angular accuracy is around 0.01°.

General features

Some general features of a LiDAR system are:

- Scanning frequency of 2.500.000 to 7.000.000 points per second
- Horizontal angular resolution 0.1° to 0.18°
- Vertical angular resolution 0.36° to 0.7°
- Dimensions 10 cm (length) x 10 cm (width) x 8-13 cm (height)
- Frame rate is 10 or 20 Hz
- Return mode of laser pulse can be
 - single return (last/strongest/first) or
 - dual return (last and strongest/last and first/first and strongest)
- Weight from 500 to 2000 gr.
- Embedded Inertial Measurement Unit system (to measure orientation of the object)

Figure 9 shows some different systems of manufacturers: Seyond (Robin W), Hesai (XT32) and Ouster (OS1 and OS Dome). The company Visimind [source: visimind.com/products] offers all these LiDAR scanners. In Table 2 more detailed information is given of these LiDAR scanners.



Figure 9 - LiDAR systems: Robin W, XT32, OS1 and OS Dome

2.3.2 Applications of LiDAR

Visimind provided a point cloud of a sail boat that was generated by a long range (Velodyne Alpha prime) LiDAR system. Although these point clouds were produced by a long range LiDAR system with different resolution and accuracy to close range systems, it shows that a LiDAR can measure the flying sail shape of a yacht from a distance of 100 m. See Figure 10 for an impression of a point cloud of the sails.

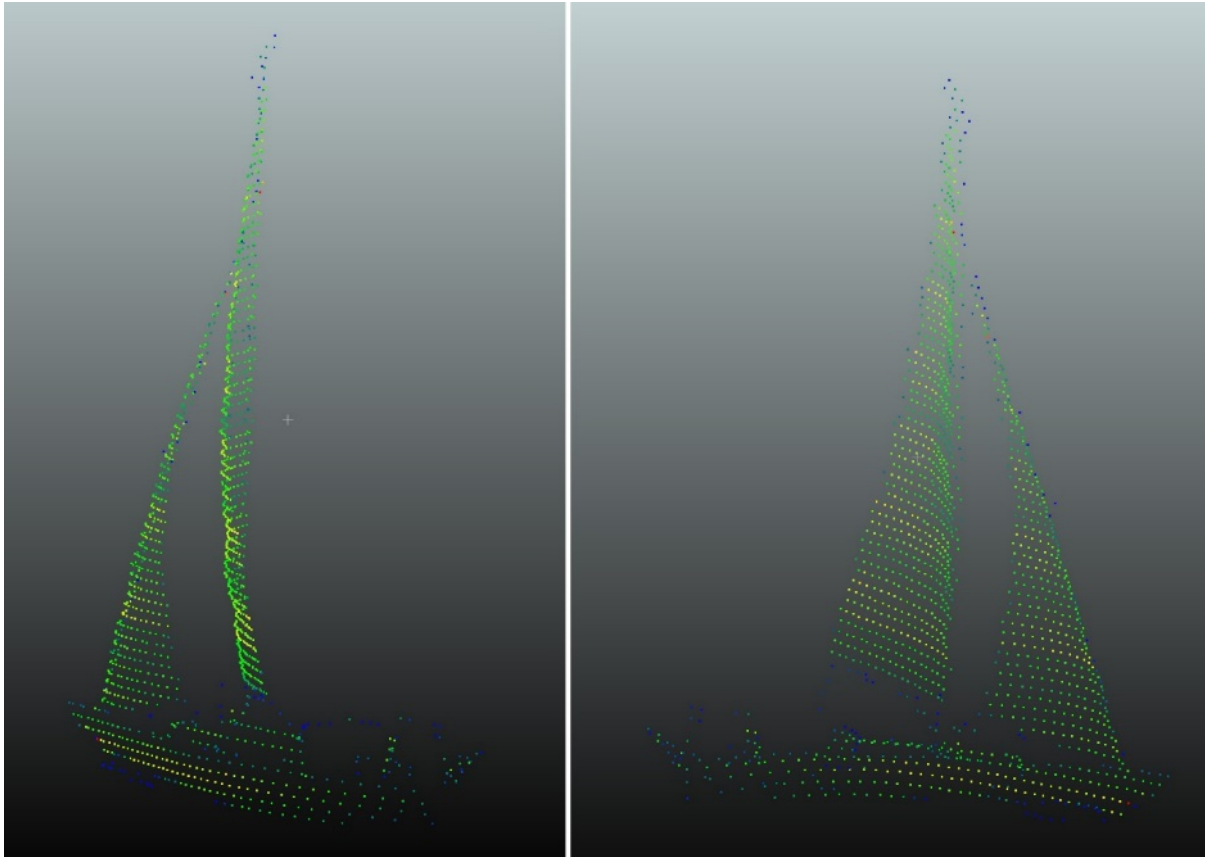


Figure 10 - 3D point cloud of a flying sail shape captured by a long range LiDAR system.

Close range LiDAR is already applied for sail shape detection, for example in the America's Cup [source: yachting.ai/blog/2024-02-11-LiDAR-in-the-americas-cup]. The LiDAR system is mounted on the deck, see Figure 11. Some systems are tilted, others are vertical mounted to the deck or on an extended support beam.



Figure 11 - LiDAR-instrument onboard. (source: <https://www.cupinsider.com/p/LiDAR-in-the-americas-cup>)

3 Applications for on a large sailing yacht

3.1 Available techniques for sail shape detection

In this part a review will be given of the possible photogrammetric techniques to measure a 3D flying sail shape. Different techniques are already available on the market. A summary of different photogrammetric techniques is listed below.

First, single camera systems are discussed, in which a 3D sail shape is determined from a single image. Second, multiple-camera photogrammetric systems are discussed, that use overlapping images to obtain a 3D point cloud of the sail shape.

3.1.1 Single-camera image system

Single camera systems attempt to infer the 3D sail shape from a single image of the sail. A single image however is not enough to obtain a 3D measurement, and doing so requires some additional assumptions. For a single camera system this is often achieved by observing the curvature of speed stripes (horizontal, coloured stripes in the sail) in the image. A perfectly straight line would represent a straight sail. Due to the increase in camber of the sail, the curvature increases. Based on several assumptions, such as distance between camera and speed stripe, the value for camber can be estimated from the curvature.

To do this, the camera needs to be positioned on the deck looking up towards the top of the sail, capturing the entire sail in one frame. Also, the distance between the camera and the location where speed stripes meet the mast needs to be known. Combined with the pixel size on the image chip and the focal distance (Figure 3), the pixel scale can be computed. This results in a value in meters per pixel. Now the camber can be estimated by counting the number of pixels between the curved line and the chord connecting both ends (Figure 12).

The presence of speed stripes at different heights in the sail is thus essential for a single-camera image system, providing the curvature at different heights in the sail. The output per stripe of this single-camera image system will be (Figure 12):

- camber
- draft
- entry and exit angles
- the twist angle of the stripe relative to boat centreline

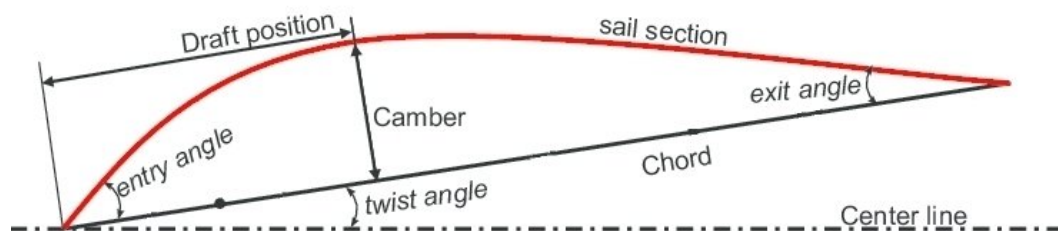


Figure 12 - Cross section diagram of a sail (red line) with relevant characteristics. [source: SailVis, Mu et al..]

Single-camera image systems are already on the market. Two systems are available and mentioned briefly.

Vspars

Vspars is a system that uses deck-mounted cameras to infer 3D sail shape from single image of the sail, based on speeds stripes. Vspars [source: www.vspars.com/rig.aspx] mentions a precision of less than 5 mm resolution at 30m. Vspars uses GoPro HERO3 and Pentax WG-1 waterproof cameras.

SailPack-Vision (BSG Développements)

SailPack-Vision [source: www.bsgdev.com/CMS3/index.php/menuproducts/sailpack-vision] is a software tool that measures the upwind flying shape from an image.

Conclusion

A single-camera image system on a large yacht could work sufficiently enough to measure the flying sail shape with a single image by using a fixed camera and speed lines with markers in the sails. The length of all the speed lines should be known. The disadvantage of this system is their low accuracy (despite the reasonable precision). Although the method of counting pixels is straight forward, it relies on the assumption that the scale is constant around the speed stripe, which is not the case. With increasing curvature, this will lead to increasing bias in the measurement. Another point is the sensitivity to weather conditions for generating reliable images, as a deck-mounted camera can easily be compromised by water drops or sun glare.

3.1.2 Multiple-camera photogrammetric system

Multiple-camera systems operate by simultaneously taking two (or more) images of a flying sail from different locations onboard and subsequently using a photogrammetric software and a scale to compute a 3D point cloud of the sail. Because a true 3D reconstruction is made, the problem of changes in scale that hold for single camera systems can be overcome.

For a multiple-camera system to work, well observable features are needed, as described in section 2.2.1. Features can be created in several ways:

- Adding cross markers to the speed stripe
 - o Advantage: easy adaptation to the sail if stripes are already present
 - o Disadvantage: no full coverage of points over the sail
- Adding well detectable markers or barcodes on the sail
 - o Advantage: full coverage of the sail
 - o Disadvantage: disturbs the visual presentation of the sail
- Relying on natural contrast differences on the sail
 - o Advantage: works without any adaptation to the sail
 - o Disadvantage: no influence on where points are found

Each of the options above leads to visible markers on the sail, potentially compromising aesthetics. A possibility to overcome this issue is to apply infrared markers that are visible to the camera but not to the human eye.

Stereophotogrammetry using any of these methods in yachting is not available yet. Experiments are being performed; two will be mentioned below. Both experiments rely on the principle of adding markers to the sail.

Photomodeler (Eos Systems)

Deparday et al. (2016)² tested photogrammetry by using 6 cameras and square blue markers in a downwind sail (spinnaker). The results show that the 3D flying shape of the spinnaker can be obtained by using the photogrammetry software PhotoModeler. Additional measurements on board are added to ensure the correct scale. The precision in the horizontal plane is around 1 cm, and just below 3 cm in the vertical direction.

Digital Telltales (Geodelta)

Geodelta tested a two camera system (called Digital Telltales) with Olympic dinghy boats, taking images from the coach boat. The results give a 3D point cloud of the flying sail³. The accuracy of the 3D point cloud is approximately 15 millimetres. Background information on the Digital Telltales project is provided in the annex.

3.2 Application of photogrammetric methods on a large yacht

This section discusses the design of an onboard close-range system to capture the 3D sail shape on a large sailing yacht using photogrammetric principles. Due to the deformation of the sail and mast, the images from different cameras need to be taken simultaneously. On a large yacht, the position and orientation of the two (or more) cameras will be fixed and known in a '*boat reference system*'. This will be an advantage for the scale, rotation and transition from the '*image-coordinate system*' to '*boat coordinate system*'. Automatically detectable circular barcodes or markers can be used as Control Points.

Requirements of the cameras

The cameras need to be contained in a waterproof case, with power supply and data storage to a device onboard. The cameras also need to be calibrated to obtain the following parameters for each camera. Table 1 shows the calibration parameters of one of the cameras used in the Digital Telltales project.

For the Digital Telltales project two Sony RX0 cameras were used. This kind of camera is also used by VSPARS, and would be an option for a photogrammetric system on a large yacht. Other possibilities are GoPro Hero or Pentax WG digital cameras.

The calibrated cameras need to have a fixed focal distance (no zoom lens can be used) and the internal software should be simple and not make any changes to the images. With the parameters of a calibrated camera (see Table 1), each image can be used for photogrammetry, see Figure 3.

Table 1 - Camera specifications of Sony RX0

Image size (horizontal)	13.1 mm, (4800 pixels)
Image size (vertical)	8.8 mm, (3200 pixels)
Pixel size	2.74 μm x 2.74 μm
Focal Length	9.069 mm
X principal point	0.001 mm

² Julien D. Deparday, Patrick Bot, Frédéric Hauville, Benoît Augier, Marc Rabaud. Full-scale flying shape measurement of offwind yacht sails with photogrammetry. Ocean Engineering, 2016, 127, pp.135-143. 10.1016/j.oceaneng.2016.09.043. hal-01379626

³ D. Mu, M. Pieras, D. Broekens, & R. Marroquim / SailVis: Reconstruction and multifaceted visualization of sail shape. Eurographics, 2021 DOI: 10.2312/evs.20211049

Y principal point	-0.012 mm
Radial Distortion Coefficient A1	$-0.1536 \cdot 10^{-4}$
Radial Distortion Coefficient A2	$-0.1304 \cdot 10^{-5}$
Polynomial zero crossing	3.945mm

Position and orientation of the camera's

On a large yacht, cameras could be placed throughout the deck to cover all the sails with overlapping images. The positions of these cameras need to be researched depending on the sails and camera lens angle, but the basic solution would be installing two cameras to get an overlapping image of each sail on each tack. Figure 13 shows a schematic overview of the number and position of the cameras needed when using two cameras for each sail. This results in a total 16 cameras, 8 on each side of the boat. The main sail possibly requires an additional camera to obtain images with enough overlap. This might also be needed for the Code Zero jib.

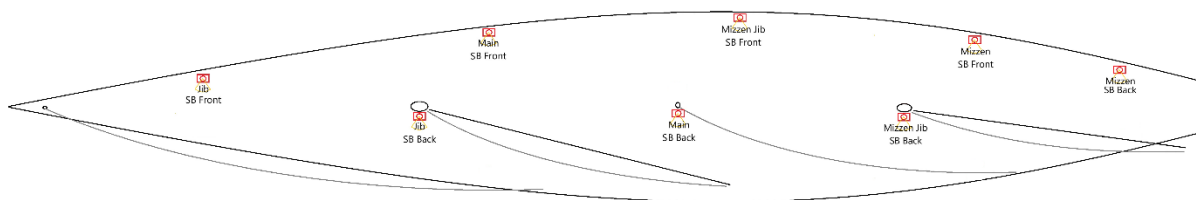


Figure 13 - A schematic overview of all the camera's needed to get all sails within an overlap for a star board tack.

All cameras will have known positions and orientations in the 'boat coordinate system', to show all sails in the same 3D point cloud. This allows integrated analysis of the sails, such as determination of the wind flow between the main and jib.

Time-synchronization

All cameras need to take images simultaneously, since both the boat and sails are moving. When the images are not taken simultaneously there will be no sharp overlapping stereopair to generate the corresponding tie points. We estimate that on a large yacht a time synchronization of tenth of a second should be sufficient.

Requirements of acquisition

The images of all the cameras can be rotated and translated into the 3D boat coordinate system. This requires fixed Control Points, that can be implemented by using markers on the deck, mast, spreaders and boom.

It is also important to select a method for defining features on the sail, as presented in section 3.1.2. When relying on natural contrast, a challenge will be to find enough tie points on the sail to reconstruct the flying sail shape with sufficiently fine-grained resolution. We therefore suggest the use dedicated markers or creating features using crosshairs on the speed stripes. This will result in the most reliable system.

The requirements for the acquisition are:

- Known positions and orientations of all cameras in the boat reference system
- Calibrated cameras
- Simultaneous acquisition of overlapping cameras
- Markers on fixed points on the boat (deck, mast, spreaders)

- Marked features on the sail using markers or crosshairs on speed stripes
- Overlapping images of the whole sail (horizontal and vertical)

Price

The following issues will influence the price of the multi-camera photogrammetric system

- The pocketsize cameras of Go ProHero 13 or Pentax WG camera are available for around 500 euros. The system requires approximately 16 to 20 cameras
- Barcodes need to be placed on the yacht to calibrate the position and orientation of all the cameras
- Collecting and processing the calibration of all cameras separately
- Investigation must take place to fix the time synchronization for all the cameras
- Investigation and research must take place to calculate the 3D point cloud for each overlapping image in real time

Recommendations for further study

When opting for multi-camera photogrammetry systems to collect a 3D flying shape we suggest to first study the following aspects in more detail:

- Research on the time synchronization of all camera's on board
- Adapting existing open-source tools (such as COLMAP) to flying sail shape in real time
- Final detailing on the camera positions and orientations to get overlap of all sails
- Final detailing on the camera settings to reduce overexposure and reflection of the sun while sailing
- Research of the position of the markers or barcodes on the yacht in a boat reference system
- Investigate solutions for lighting the sail if operation without sunlight is required
- Research on problems caused by the environment such as salt water

Overall, photogrammetry provides a solution at relatively low cost and high precision. However, the solution is dependent on natural light and therefore the results will be influenced by environmental circumstances. Photogrammetry at night is not possible without very strong artificial light.

3.3 LiDAR on a large yacht

For collecting data of a sail with LiDAR, the following parameters need to be taken into account.

Horizontal field of view

Depending on the sensor system the horizontal field of view varies from 100 to 360 degrees. With 360 degrees both tacks can be collected with the same scanner. Otherwise, two scanners need to be used to scan each tack.

Vertical field of view

Depending on the sensor system this varies from 22,5 to 180 degrees. A scanner could be mounted on the deck with a vertical field of view from just (above) horizontal to (almost) zenith. Another option is to place scanners on the mast or spreaders to obtain a view of the top part of the sail and mast. Alternatively, scanners could be mounted with a rotation of 90 degrees to obtain a bigger vertical field of view.

Range

For application on a large yacht a short-range scanner will be sufficient. The range of short-range scanners vary 30 tot 400 m. Preferably there would be one sensor scanning the total range of the mast.

Different LiDAR sensors

Table 2 shows a selection of LiDAR sensors available on the market. The Robin W shows the best field of view and range for use on a large yacht when mounted on the deck. The OS Dome will be best when mounted on the mast due to its large field of view. The alternatives would also be interesting to investigate. The range, field of view, price and accuracy are the main differences.

Table 2 - LiDAR scanners

LiDAR system	Robin W	XT32	XT32M2X	OS0	OS1	OS Dome
Manufacturer	Seyond ¹	Hesai ²	Hesai ²	Ouster	Ouster	Ouster
Hor. FoV (degr.)	120°	360°	360°	360°	360°	360°
Ver. FoV (degr.)	70°	31°	40°	90°	43°	180°
Range ³ (m)	70m	80m	120m	35m	90m	20m
Distribution	uniform	uniform	uniform	uniform	uniform	-
Channels vertical	192 ⁴	32	32	128	128	128
Resolution (HxV)	0.1°x0.36°	-	0.18°x1.3°	-	-	V: 0.7°
Angular Accuracy	-	-	-	±0.01°	±0.01°	±0.01°
Range Accuracy	± 5cm	±1cm	±1cm	± 2,5 cm	± 2,5 cm	± 2,5 cm
Range Precision (1σ)	-	0,5 cm	0,5 cm	4 cm	3 cm	10 cm
Point rate (pts/s)	-	640,000 ⁵	-	5,242,880	5,242,880	5,242,880
Weight	770 gr	800 gr	490 gr	500 gr	500 gr	470 gr
Power Consumption	9W	10W	10W	14-20W	14-20W	14-20W
Price (€)	4.300	3.500	5.800	6.000	12.000	7.000

^{1,2} Made in China ³Range at 10% reflection. ⁴Manufacturer mentions Number of lines not channels. ⁵@Single return [source: Visimind, Hesai, Seyond and Ouster website]

Position and orientation of the sensors

Figure 14 shows a schematic overview of possible placement of LiDAR sensors on board, using one scanner for each sail. In Table 3 the field of view is calculated for these positions to get an idea of how many scanners are needed to cover all the sails.

The LiDAR scanners work with local coordinate systems. Combining the point clouds of each scanner can be done by calibrating the LiDAR scanners in the boat coordinate system.

Table 3 - Position and angles of LiDAR sensors

	Jib	Main	Mizzen Jib	Mizzen
Position sensor	In front of main mast	In front of traveler main sheet	In front of mizzen mast	At the back
Horizontal angle	>315 degrees	>260 degrees	> 315 degrees	220 degrees
Vertical angle	90 degrees	90 degrees	90 degrees	90 degrees

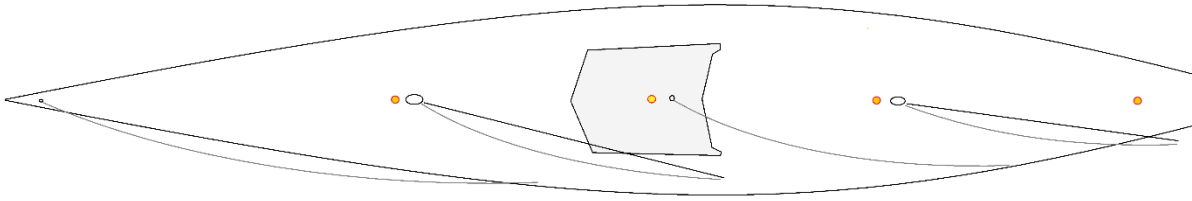


Figure 14 - Schematic overview of LiDAR sensors, 4 LiDAR sensors dependable on field of view and obstacles onboard.

The vertical field of view seems to be the limiting option in combination with the range. A solution can be to mount a sensor in the mast or spreader to obtain a view of the top half of the sail. Alternatively, sensors can be mounted on each side of the boat for a single sail, depending on the tack. Figure 15 shows the 70 degrees vertical field of view when the LiDAR is mounted on the edge of the deck.

Price

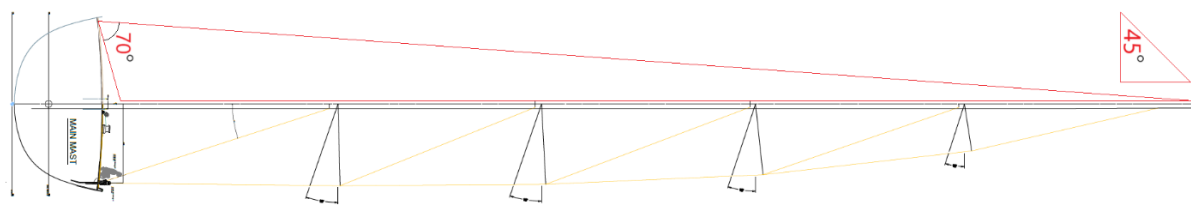


Figure 15 - Schematic illustration of 70 degrees vertical field of view from edge of boat to top of mast. Dimensions from sail plan.

Table 2 shows the prices of the LiDAR sensors. The Robin W LiDAR system costs about 4500 euro. Four sensors could be sufficient to cover all sails. The four point clouds can be merged if the position and orientation of the sensors is known in a local coordinate system.

Recommendations for further study

The use of LiDAR in sailing to collect a 3D flying shape is in development. Some challenges remain for the application on a large yacht:

- Selection of the LiDAR system and their location, in particular with respect to range and field of view
- Final detailing on the number of sensors needed to cover all the sails
- Testing of the reflection of a LiDAR on the sailcloth of the Zero sails
- Testing of the reflection of the top part of the sails
- Calibrate the positions and orientations of the LiDAR sensor in boat reference system
- Research whether it works in all weather conditions
- Research on whether (salt) water may cause any problems

3.4 Automatic Telltales Detection

In addition to photogrammetric system and LiDAR, each providing full 3D information on the sail shape, we propose a third alternative method to directly evaluate the trim of a sail.

Conventionally, the main tool for sailors to trim the sails are telltales: small rope indicators on the sail that show whether the air flow along the sail is efficient. When the telltales stream consistently (laminar) with the wind, this indicates that the sail's shape is ideal for the given conditions, including wind, waves, currents, and the type of boat. If the telltales are fluttering or pointing upwards or downwards, this is an indication of turbulent or suboptimal airflow, and a change of course or trim is required.

In Figure 16 the telltales in the left figure show a nice flow and the telltales in the right figure show turbulent flow, indicating that the sail trim needs to change. Using telltales requires skilled sailors that pay constant attention and have the telltales in sight - conditions that are not always met. Automatic detection of telltales could provide a way to assist crew in this process.

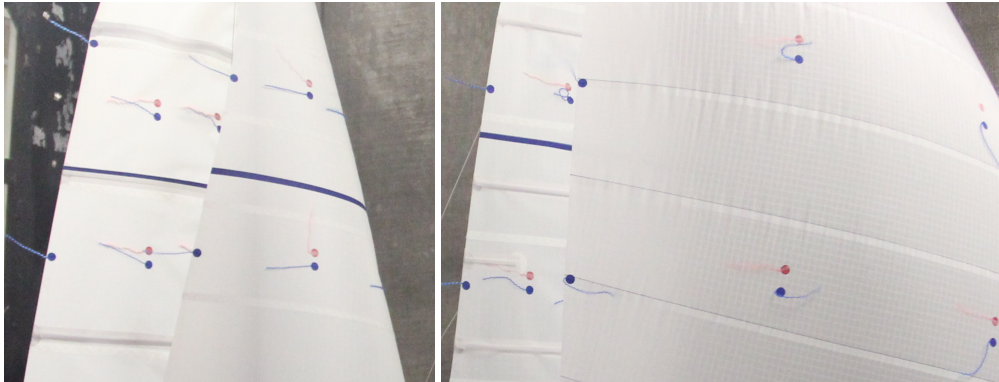


Figure 16 - Telltales show the wind flow on different spots on the sails.

Using a single-camera system for one sail and taking multiple images over time, the telltales can be tracked automatically and give information on the sail trim. The information in the obtained images (see Figure 17) needs to be transformed to a simple output to be shown to the crew, for instance:

- Windward telltale is up, then change course to leeward;
- Leeward telltale is not straight, then loose sheet or change course to windward.

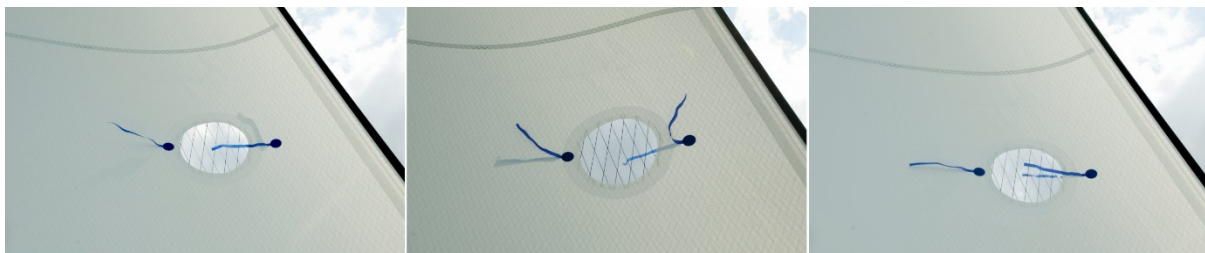


Figure 17 - Left: Losen sheet or change course to windward, Middle: tighten sheet or change course to downwind. Right: proper trim and course for this moment. [source: 'Telltales uitgelegd: de fok' in magazine Zeilen]

Output

This system will not generate a 3D point cloud as output but will give a signal to the crew to change course or change sail settings. In Figure 18 a schematic timeline is given on the output of this technique. A detailed description of how such a system would look is beyond the scope of this research.

Price

The pocketsize cameras of Go ProHero 13 or Pentax WG camera are available for around 500 euros. One camera per sail would be required. Research on the automatic detection and visual interpretation of the data need to be executed.

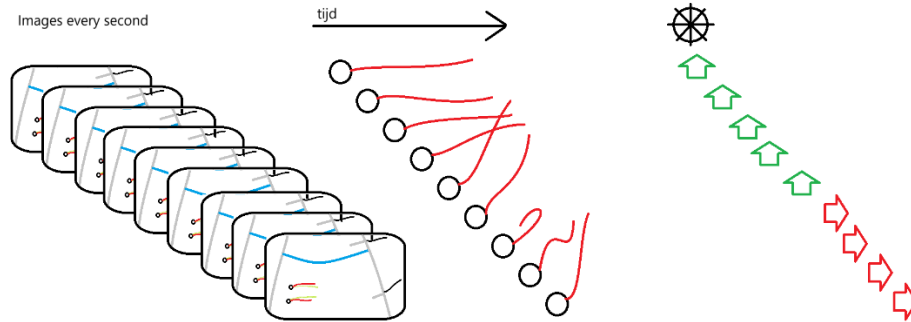


Figure 18 - Automatic Telltales Detection by one camera to detect changes in the telltales, can give a signal to the crew to change course.

Mast bend

When using a single camera for the Automatic Telltales Detection, it is worthwhile to investigate the option of automatic detection of circular barcodes on the spreaders and mast to get information about the mast bend, see Figure 19. In combination with the speed stripes as used by the single-camera systems this will give lots of extra information of the sail shape to optimize the sail trim or course.

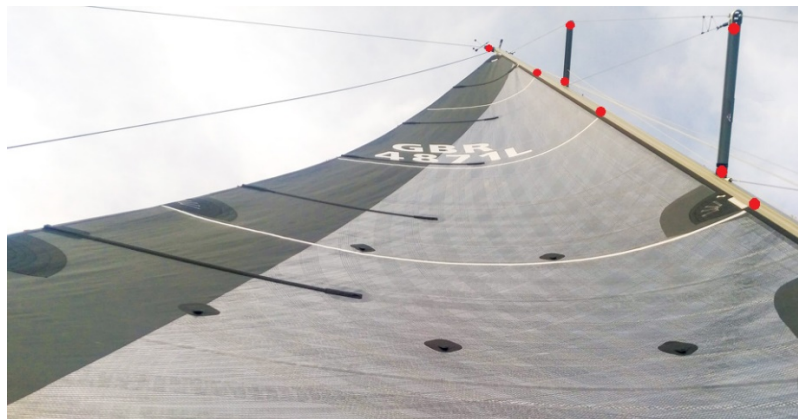


Figure 19 - With circular barcodes (red dots) on the spreader using single camera to detect the telltales, gives information about the mast bend.

Summary

Automatic Telltales Detection provides a relatively simple technique to get information on the optimal sail trim. The crew does not necessarily need to be skilled and experienced sailors. They will get a signal when the telltales are disturbed and action needs to be taken. The required cameras can also be used to measure sail parameters using the speed stripes and measure mast bend by using circular barcodes. The following aspects require more investigation:

- Research on visual detection of telltales
- Research on the camera to use
- Research on the camera positions
- Optimization of the locations of the cameras on Zero
- Calibration of camera positions and barcodes on board
- Research on the barcodes for the reference system and mast bend
- Research on the speed stripe information

4 Summary and conclusions

This chapter summarizes the different systems and concludes with the most important insights on techniques for sail shape detection for yachting or other techniques to optimize sail trim.

4.1 Summary

Two different techniques for generating 3D point clouds are discussed: photogrammetry and LiDAR. The LiDAR system provides a point cloud for each sail. Multi-camera photogrammetry also provides a point cloud, but innovation is needed to optimize this process, in particular in synchronizing and calibrating onboard cameras, and post-processing the images.

Single-camera systems were also discussed, which are readily available on the market. Their operation depends on the curvature of speed stripes in the sail, and they offer a limited 3D reconstruction of a 2D image.

The Automatic Telltales detection does not provide information on the sail shape but rather an indication of the flow along the sail. This information could be directly used to develop a system that indicates when the trim needs to be adjusted. Table 4 provides an overview of the following systems:

- Single-camera system
- Multiple-camera photogrammetry system
- LiDAR system
- Automatic telltale detection

Table 4 - Summary of the different systems

	Single-camera system	Multiple-camera photogrammetry system	LiDAR system	Automatic telltale detection
Non-contact technique	Yes	Yes	Yes	Yes
Use of markers needed	Yes	Yes	No, only when multiple systems are mounted in the mast, with varying positions due to mastbend.	No
Calibrate camera	Yes	Yes	No	No
Investigate position and orientation of camera	Yes	Yes	Yes	Yes
Control Points are needed	Yes	Yes	No	No
Use a boat reference system	Yes	Yes	Only for merging multiple points clouds	No
Develop system for simultaneously taking images	No	Yes	No	No
Accuracy	High but limited due to assumptions on curvature	High	High	Not applicable
Night conditions	No, possibly infrared works	No, possibly infrared works	Yes	Maybe

Output: 3D point cloud for each sail	No	Partly, needs development	Yes	No
Output: 3D point cloud of all sails	No	Partly, needs development	Yes	No
Output: Automatic telltale detection	Optional	Yes	No	Yes
Output: Speed stripe curve	Yes	Yes	Maybe	Optional
Output: Mast bend	Yes	Yes	Maybe	No

4.2 Conclusions

4.2.1 Single camera systems

Single camera systems depend on markers and/or speed stripes and are fundamentally limited in that they only provide information on the curvature of the sail in a fixed number of places. They also face practical challenges of sensitivity to weather conditions and light. However, they are readily available in the market and do provide information on the sail shape in the form of parameters that are directly interpretable to the crew.

4.2.2 Lidar vs multi-camera photogrammetry

LiDAR and multiple-camera photogrammetry both generate a 3D point cloud. However, the application of a multiple camera photogrammetry system on a large yacht would require development in the following areas:

- Placement of markers to obtain a sufficiently dense point cloud
- Sensitivity to weather conditions and light
- Infrastructure for calibrating and synchronizing cameras

LiDAR systems on the other hand are developing very fast in different industries and directly generate a 3D point cloud at high accuracy, with less sensitivity to conditions and light. Also, LiDAR systems have a wider field of view, requiring less hardware.

Both techniques provide a 3D point cloud, which is the most accurate description of the state of the sail but requires processing to inform a crew on sail trim. The generated data could be used for analysis or be process for instance by a machine learning algorithm. A key ingredient for such analyses would be to obtain a target shape for each condition. Alternatively, relevant parameters (such as camber of angle of entry) on sail trim that are interpretable by crew could be derived from the point clouds. How to do this is beyond the scope of this report but is without question a challenge in itself.

4.2.3 Automatic telltale detection

Automatic telltale detection could provide a way to leverage the proven technology of telltales, aiding a crew in reading them. The output provides information on the flow along the sail as opposed to its shape, and hence is more easily interpreted by the crew.

This system can also very well be used in combination with one of the systems that provide information on the sail shape, as it provides complementary information to the sail shape. Combining systems would allow relating the detected sail shape to the wind conditions and flow along the sail, which could lead to identification of target shapes and a more complete picture on how to achieve the sail shape that results in an optimal boat speed.

Attachment Digital Telltales Results

Digital Telltales on the Laser dinghy

Olympic sailors want to trim the sail as good as possible to maximize their speed. They are trained to optimize sail trimming and steering for each weather condition. One way to do this is to look at the telltales in the sail(s). On different locations in the sail and at the leech telltales can provide the sailor with information about the wind flow along the sail and the sail trim (draft and camber) of the sail.

In this Digital Telltales project the first goal was to test whether photogrammetry could be used to measure the sail shape (of an Olympic Laser dinghy). The second goal was to test if it was possible to measure differences between different sail shapes using photogrammetry, see Figure 20. Both goals were tested positive.

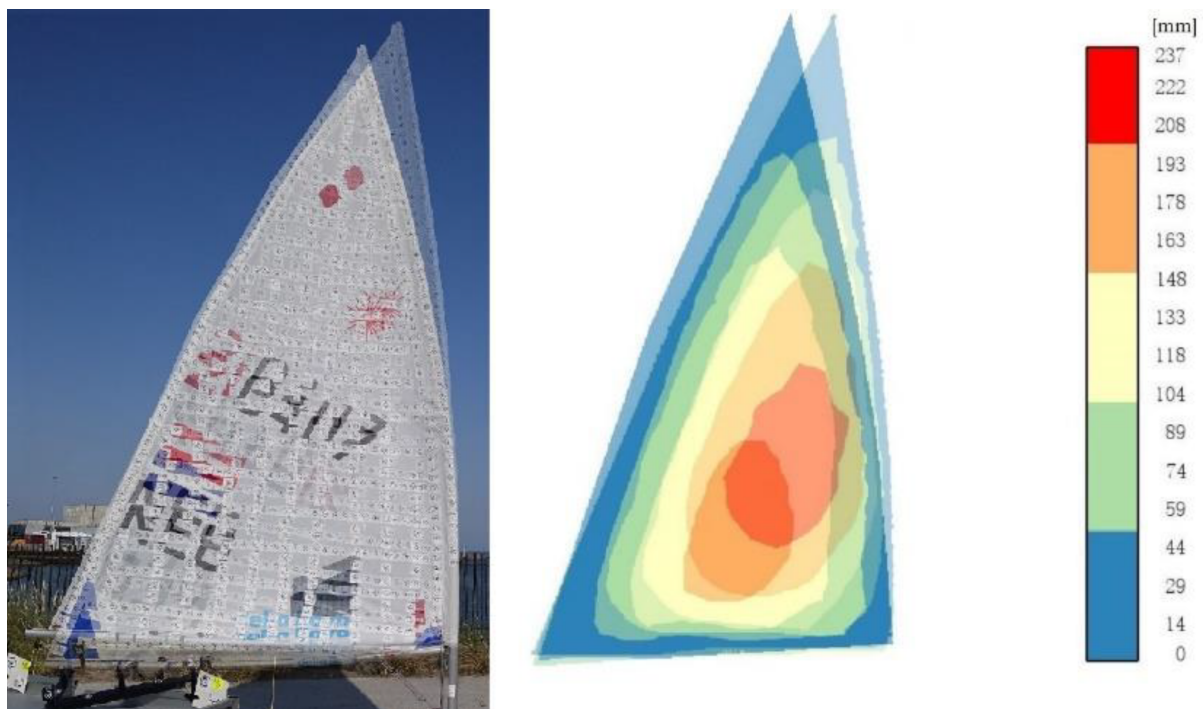


Figure 20 - Two different sail trims were measured by using photogrammetry. Markers in the sail were automatically measured to generate a 3D shape.

The third goal was to research if it is possible to use photogrammetry to measure different trims of flying sail shapes. This is also tested positive; an accuracy of 15 millimetre or better was achieved. But some issues still need to be investigated for better solutions. The following research questions are still to be answered.

- Approximately 80% of the barcodes were detected automatically. Gaps with no data occurred due to
 - brightness of the sun in the sail or in the background
 - reflection of the sailcloth or barcodes
 - sailor covers lower barcodes
 - no full overlap of the whole sail (cameras too close to dinghy)

Figure 21 shows different images with different weather conditions. Would it be possible not to use barcodes and still obtain enough tie points to calculate a 3D point cloud?



Figure 21 - Barcodes, sailcloth and sunlight reflects differently each moment.

- Would it be possible to only use speed stripes in the sail and obtain the curve of the stripes and the 3D flying sail shape?
- Is it possible to make the measurements (almost) real-time?
- When fixed cameras on big boats will be used the rotation and translation problem from different images (taken on different locations and distance of the Laser dinghy) will be solved. Would Digital Telltales work on big boats using mounted cameras and just some markers to obtain the scale?

Scan of a Laser

During the experiment of Digital Telltales making images of the Laser-sail, also LiDAR was tested. In Figure 22 the results of a LiDAR measurement is shown. In this case the sail dinghy was inside a building and the instrument was mounted on a tripod and no wind was disturbing the sail. The LiDAR system is a high accurate instrument normally used for land surveying. The point density is very high, the angle of view is 360 degrees, the accuracy is high. This is not representative instrument to use on board of a yacht.

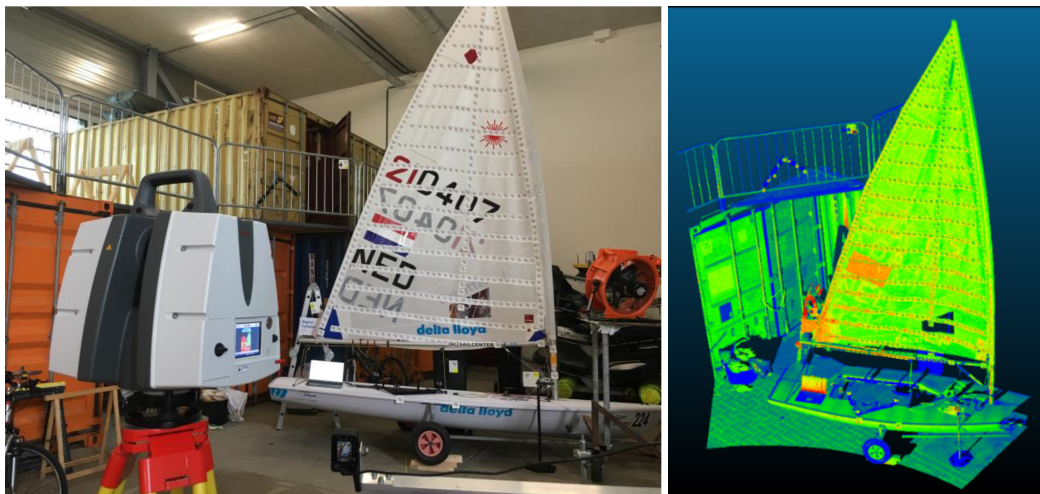


Figure 22 - LiDAR results of the Olympic Laser dinghy.