A reverse engineering approach to measure the deformations of a sailing yacht

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Abstract In this work, a multidisciplinary experience, aimed to study the permanent deformations of the hull of a regatta sailing yacht is described. In particular, a procedure to compare two different surfaces of the hull of a small sailing yacht, designed and manufactured at the University of Palermo, has been developed. The first one represents the original CAD model while the second one has been obtained by means of a reverse engineering approach. The reverse engineering process was performed through an automatic close-range photogrammetry survey, that has allowed to obtain very accurate measures of the hull, and a 3D modelling step by the well-known 3D computer graphics software Rhinoceros. The reverse engineering model was checked through two different procedures implemented by the graphical algorithm editor Grasshopper. The first procedure has allowed to compare the photogrammetric measurements with the rebuilt surface, in order to verify if the reverse engineering process has led to reliable results. The second has been implement to measure the deviations between the original CAD model and the rebuilt surface of the hull. This procedure has given the possibility to highlight any permanent deformation of the hull due to errors during the production phase or to excessive loads during its use. The obtained results have demonstrated that the developed procedure is very efficient and able to give detailed information on the deviation values of the two compared surfaces.

Keywords: reverse engineering; close range photogrammetry; CAE tools; sailing yacht; generative algorithms.

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1 Introduction

After a boat has been constructed and used, differences in shape and dimensions can occur due to production defects and/or excessive loads during use. The measurement of these differences represents a very important task because they have direct impact on boat speed, stability, strength and efficiency [1].

Two different approaches can be used to reconstruct the real hull shape of a boat: a direct method and an indirect (or non-contact) one [2]. Using the first approach, based on manual measurement tools, a direct contact with the boat is needed. This kind of method, even if not more expensive and rather flexible, usually does not produce very accurate results, especially for large-dimensions objects. Indirect approach, instead, does not require any contact between measurements tools and boat hull [3]. Most common techniques used for non-contact reconstructions of 3D objects [4-8] are based on laser scanning systems and photogrammetry methods.

Photogrammetry allows to determine the size and the shape of an object by analyzing recorded images. In particular, close-range photogrammetry is the technique usually used in reverse engineering processes [9]. Many studies have demonstrated that close-range photogrammetry is a very accurate and low-cost method and, in many applications, can have comparable performances to laser scanning methods and coordinate measuring arms [10-11]. For these reasons, close-range photogrammetry, also thanks to recent informatics, technological and software improvements, has become more and more widespread and has been largely used in different application fields (like structural monitoring, engineering and manufacturing, cultural heritage, quantifying landform change, etc.).

In this paper a reverse engineering process has been carried out to reconstruct the shape of the hull of a small sailing yacht with the aim to measure its deformations after several regattas. The main objective of the work is to demonstrate that deformations measurement can be made in a very fast and accurate way through automatic digital close range photogrammetry and automatic processes developed using *Grasshopper*, an advanced visual programming environment for *Rhinoceros 3D*. The close range photogrammetry has been used to measure the real shape of the hull with an accuracy of about ±0.1 mm; then, a 3D modeling process has been performed to reconstruct the hull's surface. Two different procedures have been implemented in *Grasshopper* to check the 3D model as regards photogrammetric measurement and to compare the 3D model with original CAD model.

2 Case study

A small sailing yacht (i.e. a dinghy), designed and manufactured at the University of Palermo has been surveyed (Fig. 1 left). The hull shape of the analyzed sailing yacht has been defined following a simultaneous design approach [12-13]. In particular, CFD codes and analytical resistance prediction models have been simultaneously used in order to find the optimal hull shape for a given sailing condition (close-hauled in a breeze). The CAD model of the hull has been firstly created by setting typical design ratios (e.g. prismatic coefficient, beam to length ratio) and refined identifying two mutually set of curves (Fig. 1 right) perpendicular one each other (the so called waterlines and sections) used to define the hull surface.

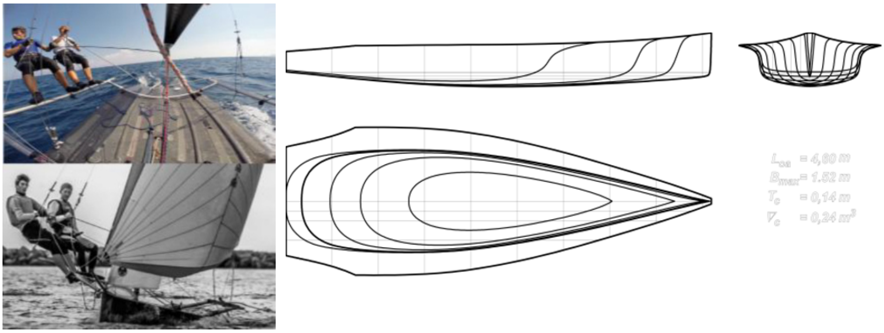


Fig. 1 -Crew over the wing of LED during regattas (left); yacht lines plane (right)

3 Reverse engineering model: *the photogrammetric survey*

The use of close-range photogrammetry in reverse engineering and manufacturing applications is not new because this technique is one of the main approaches to get accurate, precise and reliable 3D data. Applications are typically carried out in scenarios where it is necessary to have measuring accuracy in the range of a few tens of micrometers to tenths of a millimeter and where object size is in the range 1-10 m [14]. In this context close range photogrammetry is a very powerful technology that allows the development of fully automated pipeline and get performance comparable with active range sensors (e.g. short-range laser scanner).

The reverse engineering surface of the hull was obtained by an automatic close-range photogrammetry survey following the typically photogrammetric workflow: camera network design, camera calibration, automatic images orientation and points measurement by coded and non-coded targets, accuracy evaluation.

For the hull's survey a very strong convergent camera network was planned by turning around the hull from three different path; every path was planned from a diverse high but at the same average distance from the hull (about 1.5 meters) (Fig. 2). The images from the highest level were repeated three times, once by taking the images with the camera in landscape position, the other rotating the camera in the portrait position (±90°).

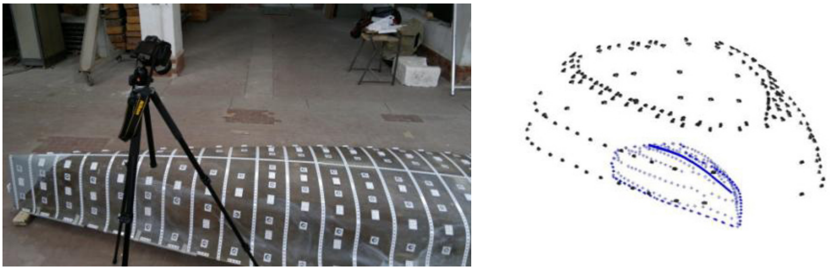


Figure 2 - Image acquisition (left) and camera network (right)

In all 169 images of the hull were taken with a digital camera Nikon D5100 equipped with a 35 mm Nikkor AF-S f/1.8G fixed focus lens; the camera has a CCD sensor with size of 23.6 mm x 15.6 mm, a pixel size of 4.8 μm and an effective resolution of 4928 pixels x 3264 pixels. The image scale was 1/43 and the coverage of each image was about 1.0 m x 0.7 m. Because the camera focal length was 35 mm, each pixel was about to 0.21 mm in the object space.

The photogrammetric survey was used to measure 23 profiles and many feature details of the hull. The profiles and the details were indicated by non-coded targets that were automatically detect and measured by the photogrammetric system. Their positions have been chosen in accordance with the positions of the profiles used to generate the CAD model. About 200 coded targets were also putted on the hull to automatically orient the images. Ten calibrated scale bars, with two calibrated distances measured with a computer numerical control machine and with an accuracy of ±20 microns, were placed along the edge of the hull; the calibrated scale bars were used to scale the photogrammetric model and to check the accuracy of the survey. The use of calibrated scale bars is very frequent in the field of industrial applications to scale the photogrammetric model because it allows to obtain accuracy in the order of few tens of micrometers [15].

The accuracy evaluation of the photogrammetric project shows maximum images residual of 0.5 pixel and scale bars precision with RMS of ±0.024 mm; the independent check performed with the calibrated distanced not used for orientation shows a RMS value of ±0.018 mm. These results confirm the metric accuracy of the photogrammetric measurement.

The points along the profile were used to generate the reverse engineering surface, while the points over the hull were used to check the 3D model obtained during the 3D modeling phase.

4 Reverse engineering model: *the 3D modeling phase*

The preliminary phase of acquisition of the hull geometry provided a numerical model, which represented the basis for the formulation of the mathematical model. The parametric NURBS surface was generated from controllable and adjustable plane curves.

It was structured with specific morphological characteristics that allowed both a comparison with the project surface of reference, and an assessment of the punctual variations. The alignment with the project CAD model was possible after designating the stern area as reference system. During the post-processing phase, the acquired points were imported into the known NURBS modelling software Rhinoceros. The acquired points were collected and organised in several layers depending on their origin (transom, transversal sections, gunwale line, keel line) to ensure a more efficient management and an accurate control [16-18]. The points acquired during the survey, which were necessary for the creation of the main curves of the surface, were not evenly distributed. For this reason, a rigorous process of optimisation and editing of the data was fundamental (Fig. 3). Subsequently, the organised geometrical data was processed, in order to generate the isocurves fitting the acquired points. The main generated curves represented the geometrical-spatial structure of the hull surface.

The next step was to generate a loft surface that interpolated, with small variations, the grid of points acquired during the survey.

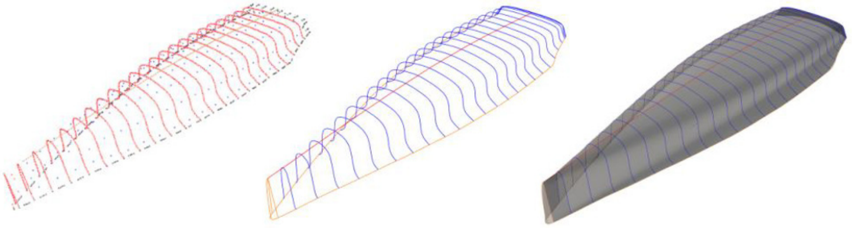


Figure 3 – Creation of the section profiles and the lofted surface of the hull

5 The analysis of the surface's hull

To analyze the hull surface, two customized procedures were developed with the Rhinoceros's plugin Grasshopper [19].

This approach allowed the implementation of a workflow, which made the modelling process of the hull parametric, and enhanced the analysis and diagnostic tools already existing within the software. It also helped learning the geometric properties of the created surfaces (typology and class, curve evolution, apparent boundary, construction origins).

The first procedure had a structure that allowed the user to calculate the deviations of the points/targets from the generated surface. This was possible after loading the geometries of the hull surface and the points/targets of the photogrammetric survey (input data) into the working environment (Fig. 4). The results were the maximum and minimum deviation values. For this case study, the set parameters provided output results with a maximum variation in the order of a tenth of a millimetre, thus validating the congruity of the created surface with the initial acquired data.

Once the reliability of the survey data was verified, the study proceeded with the formulation of a second procedure with a more complex structure. This procedure was capable of comparing the project CAD model with the one from the photogrammetric survey, while determining the surface variations, as well as the possible deformities resulting from the molding [20].

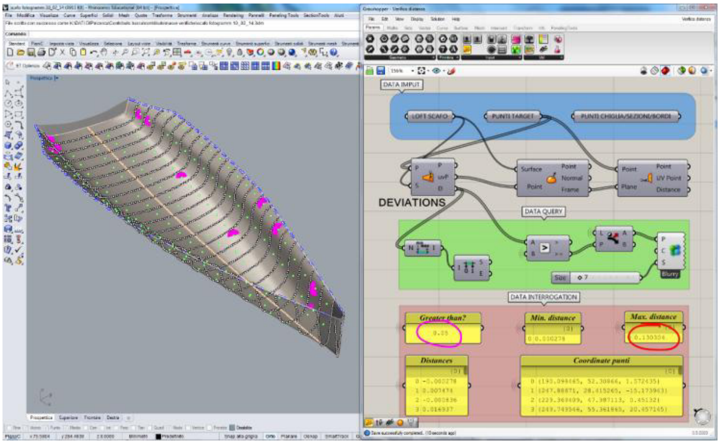


Figure 4 – Definition of the first algorithm for the calculation of the deviations of the points/targets from the generated surface, providing max and min values as results

The structure of the procedure is shown in figure 5 and its workflow is the following:

1. *Input*: during the initial sequence, both the project and the photogrammetric CAD models are loaded. Before proceeding with the data elaboration, the operator adjusts the subdivision of the surface mesh on the u and v directions (specifically, a subdivision of 200 fractions on the two directions was chosen). The function linked to this command defines the isocurves in the two directions describing the input surfaces.
2. *Distance determination*: during this phase, it is determined which shape is the one used as reference and which is the one to compare. Then, a structured grid of points is created from the intersection of the isocurves of the reference surface (specifically, a 40.000-points grid), and the distance of each point from the surface to compare is determined using a vector. Then a logic function is intro-

duced, in order to determine the sign of the value of the measured distance. From an operational point of view, an auxiliary plane was used, which was tangent to the reference surface and orthogonal to the minimum distance segment of the point on the surface.

3. *Max e min deviation*: maximum and minimum deviation values are extracted and used as extremes of a variation range of the two surface samples.
4. *Remapping for colour gradient*: a specific colorimetric value is assigned to each distance value.
5. *Output*: a legend with a range of pre-selected values is generated.
6. *Query*: the query block represents the most important element of the procedure. It includes a logic function that determines the punctual variations between the surfaces, starting from their respective u-v coordinates.

This procedure has allowed to calculate the deviations of the photogrammetric model compared with the project one; the variations are of a few millimeters (40.000-points grid; maximum deviation value: 4,26 mm; minimum deviation value: -3,60 mm) (Figs. 5-6).

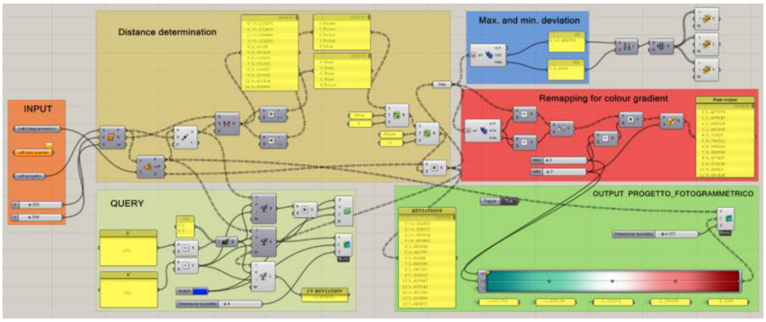
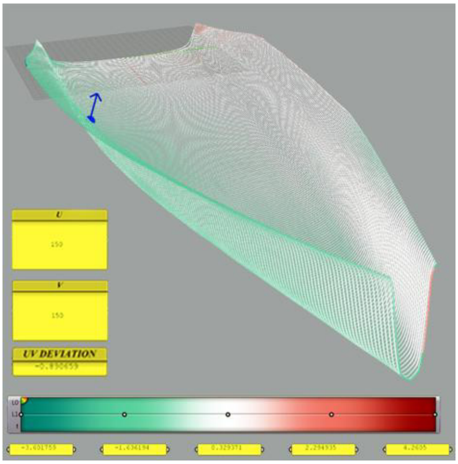


Figure 5 - Definition of the second procedure for the comparison of the project CAD model with the photogrammetric model; scheme of the operational phases



U
150
V
150
UV DEVIATION
-0.850659

Figure 6 – Determination of the punctual variation between the surfaces. Below, maximum and minimum deviation values of the real hull shape with regard to the CAD mode

6 Conclusion

The obtained results demonstrate that the developed procedure is very efficient and able to give detailed information on the deviation values of two compared surfaces. As regard the case study, remarkable differences have been noted on the real hull surface compared to the initial CAD model. These deviations could be due to excessive or asymmetric load conditions. The developed surface comparison algorithm can be used with data coming from different reverse engineering systems (laser scanner, DIC, moiré fringes based, etc.) so allowing a very large field of use. With regard to the experiences comparable to the case study, the experimental study proposes the use of customized algorithmic functions in the geometric analysis process that optimizes punctual query of the output data, ensuring a tighter control of hull deformations.

The implemented process, of course, is not limited exclusively to sailing yachts, but it can represent a very useful tool to measure, in a simple, accurate and parametric way, any dimensional and shape differences between reverse engineering acquired data and CAD models of any object.

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