Journal of Engineering and Applied Sciences 13 (7): 1638-1643, 2018
ISSN: 1816-949X

New Algorithms to Evaluate the Real Shape of a Hull

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Abstract: In this study, a new method to compare rebuilt surfaces of hulls of sailing yachts is presented. In particular, the considered rebuilt surfaces are created through classic reverse engineering approaches. The new method has been developed by means of Grasshopper, a free generative algorithms editor that can be used as plugin of Rhinoceros, one of the most widespread free-form modelling software. In particular, two different algorithms have been developed: the first one allows controlling the quality of the rebuilt surfaces, the second one, instead, allows to measure the deviations between the original CAD Model and the rebuilt surface of the hull. A case study related to the hull of a small sailing yacht is also presented. The obtained results have demonstrated the efficiency of the new proposed low-cost method.

Key words: Low-cost reverse engineering analysis, close range photogrammetry, CAE tools, sailing yacht, generative algorithms, CAD Model

INTRODUCTION

All the boats, after the production phase and a period of use a boat show differences in shape and dimensions that can occur both due to production defects and/or due to excessive loads during use. The evaluation of these differences is a very important task because they have direct impact on boat speed, stability, strength and efficiency (Brewer, 1994). The real shape and dimensions of a boat hull can be effectively obtained by means of measurements, following a reverse engineering approach. Thanks to these measurements, it is possible to investigate the hull of a boat and monitoring any deviations from the original project. Different approaches, with different level of accuracy can be used to reconstruct the real hull shape of a boat survey (Koelman, 2010). Most common are methods that makes use of conventional manual measurement tools, likes measurement tape or a laser distance meter. This kind of method, even if not more expensive and rather flexible, usually does not produce very accurate results, especially for large-dimensions objects. Mechanical devices (e.g., Coordinate Measuring Machines-CMM) could also be used and could allow to get very high level of accuracy but their use in nautical application is often limited due to size of the boats and the cost of the devices. Conventional manual measurement tools and mechanical devices could be classified direct method because they always need direct contact with the object. Indirect approach, instead does not require any contact between measurements tools and objects. Most common techniques used for non-contact reconstructions are based on active or passive sensors (Remondino and El-Hakim, 2006). Active sensors provide directly range data containing the tree-dimensional coordinates of the object, passive sensors generally provide images that need further processing to derive the 3D object coordinates (Remondino and El-Hakim, 2006); this last approach is usually defined image-based modeling. The active sensors are typically triangulation laser scanner, pattern projector sensors and time of flight or phase shift laser scanner (Wang, 2011; Blais, 2004). These devices could theoretically be used for all kind of objects but in some cases the shape and the type of material of the object could cause some problems during the data acquisition step. These problems have been pointed out in particularly in some nautical applications for the reverse engineering process of medium and small hulls (Guidi *et al*., 2005).

The most known and most used image-based technique is photogrammetry. In particular, close-range photogrammetry is the technique usually used in reverse

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engineering processes. 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 (Skarlatos and Kiparissi, 2012; Cuesta *et al*., 2012). For these reasons, close-range photogrammetry, also thanks to recent informatics, technological and software improvements has become more and more widespread. Close-range photogrammetry has been largely used in different application fields (Fryer *et al*., 2007; Agnello and Brutto, 2007) like structural monitoring, engineering and manufacturing, cultural heritage, quantifying landform change, etc. In this study, a new method to analyze hull surfaces rebuilt by means of reverse engineering analyses has been developed. 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.

MATERIALS AND METHODS

A small sailing yacht (i.e., a dinghy), designed and manufactured at the University of Palermo has been surveyed (Fig. 1).

The hull shape of the analyzed sailing yacht has been defined following a simultaneous design approach (Cappello *et al*., 2005; Ingrassia *et al*., 2014, 2017; Ingrassia and Mancuso, 2013). 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. 2) perpendicular one each other (the so called waterlines and sections) used to define the hull surface.

The reverse engineering analysis; A photogrammetric survey: To acquire the hull surface of the analyzed small sailing yacht a close-range photogrammetry reverse engineering approach has been used. Applications of close-range photogrammetry 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 (Robson and Shortis, 2007). For the hull's survey a very strong convergent camera network was planned by turning around the hull from three different path so, creating a camera network (Fig. 3); every path was planned from a diverse high but at the same average distance from the hull (about 1.5 m).

Fig. 1: The analyzed small sailing yacht

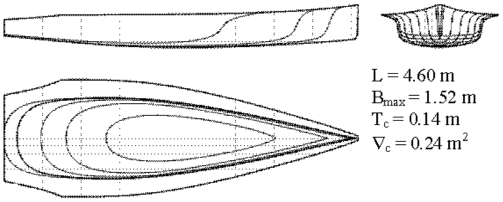


Fig. 2: Main yacht lines plane

Fig. 3: Camera network

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°). 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 23.6×15.6 mm, a pixel size of 4.8 μm and an effective resolution of 4928×3264 pixels. The image scale was 1/43 and the coverage of each image was about 1.0×0.7 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

Fig. 4: Non-coded target applied on the hull surface

hull. The profiles and the details were indicated by non-coded targets (Fig. 4) 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. 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.

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 organized in several layers depending on their origin (transom, transversal sections, gunwale line, keel line) to ensure a more efficient management and an accurate control (Di Paola *et al.*, 2015; Tedeschi, 2014; Santagati *et al.*, 2013). The points acquired during the survey which were necessary for the creation of the main curves of the surface were not evenly distributed (Fig. 5).

For this reason, a rigorous process of optimization and editing of the data was fundamental. Subsequently, the organized 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 (Fig. 6).

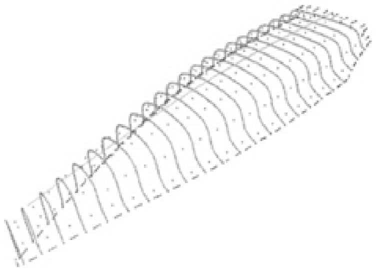


Fig. 5: Selected points after the survey

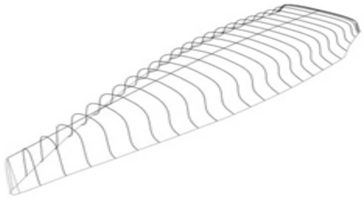


Fig. 6: Isocurves fitting the acquired points

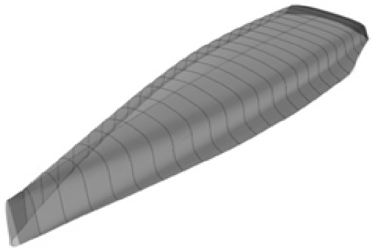


Fig. 7: Rebuilt hull surface

The typology of the generated curve was the one used for the creation of the project CAD Model: a bicubic B-spline. Initially, editing tools for the mathematical nature of the curves were used in order to control the evolution of the hull surface and avoid formal curvature imperfections, surface discontinuities or overlaps and misalignments. Such tools included: normalisation, joints with curvature continuity (G2) control, use of degree 3 curves, number of control points, coplanarity of the curves/sections. After reconstructing the section curves, we employed a series of procedural tools useful to the rigorous reconstruction of the hull (e.g., determining the number of control points for all curves, amounting to 200; normalization of curves, etc.), respecting the tolerance limits.

The next step was to generate a loft surface that interpolated with small variations, the grid of points acquired during the survey (Fig. 7). The “Loft” tool generated the result that best matched the initial data. This command for surface generation is in fact the most suitable when it comes to build a NURBS surface from a given series of adjacent profile curves.

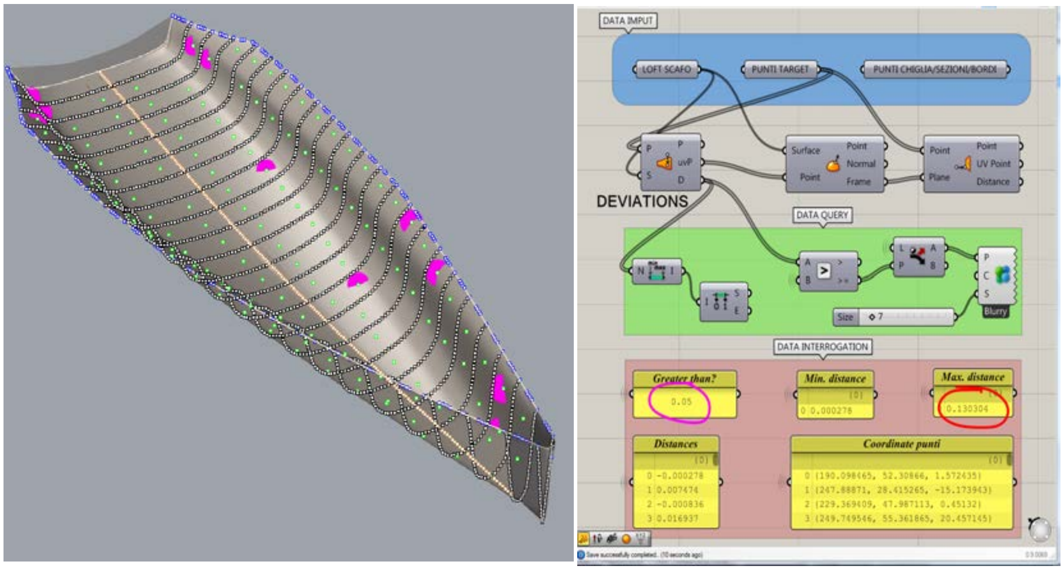
RESULTS AND DISCUSSION

The experience acquired in the multidisciplinary laboratory, during the processing of the collected data, allowed experimenting and giving structure to specific applications that enabled a rigorous control of the graphical-geometric investigation. The formulation of specific procedural algorithms enabled a more efficient and manageable measurement data exchange as well as a rigorous quality control of the complex free form geometries generated. The surface analysis revealed a departure from the points located along the keel; for this reason we proceeded to the reconstruction of the section curves by inserting other control points near the keel profile. Since, the curved sections were not coplanar, the visual analysis of continuity (map “zebra”) showed many discontinuity errors of curvature and of tangency distributed along the hull surface.

Therefore, in the next step we decided to extrapolate multiple sections from the lofted surface placed at a distance of 10 cm (the same distance of the targets strips placed on the hull during the survey). The plane curves obtained have allowed the construction of the final loft surface. To analyze the hull surface, two customized procedures were developed with the Rhinoceros’s plugin Grasshopper (Tedeschi, 2014). This led to the design of a process for the collection of specific results from certain input data, through a finite logic set of elementary instructions, entered by the operator. 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. 8).

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. The diagram of the procedure is shown in Fig. 9. The algorithm workflow is the following.



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Greater than?
0.05

Min. distance
{0}
0 0.000278

Max. distance
0.130304

Distances
{0}
0 -0.000278
1 0.007474
2 -0.000836
3 0.016937

Coordinate punti
{0}
0 {190.098465, 52.30866, 1.572435}
1 {247.88871, 28.415265, -15.173943}
2 {229.369409, 47.987113, 0.45132}
3 {249.749546, 55.361865, 20.457145}
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Fig. 8: On the left the points/targets used to perform the measurement, on the right the block diagram of the first developed algorithm

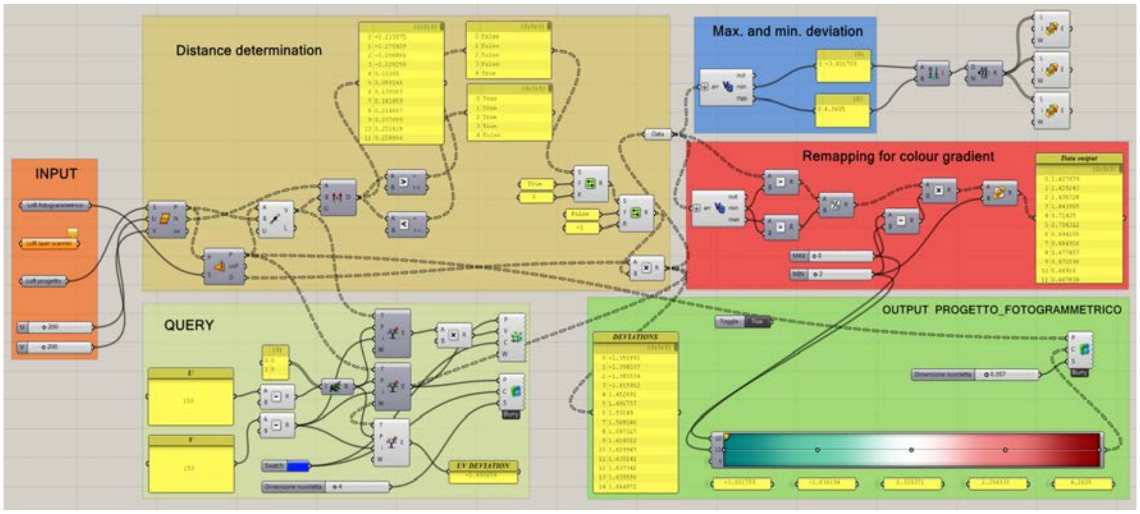

Fig. 9: The block diagram of the second developed algorithm

- 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
- 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 introduced, 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 (Fig. 10)
- Max E min deviation: maximum and minimum deviation values are extracted and used as extremes of a variation range of the two surface samples
- Remapping for colour gradient: a specific colorimetric value is assigned to each distance value
- Output: a legend with a range of pre-selected values is generated
- 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

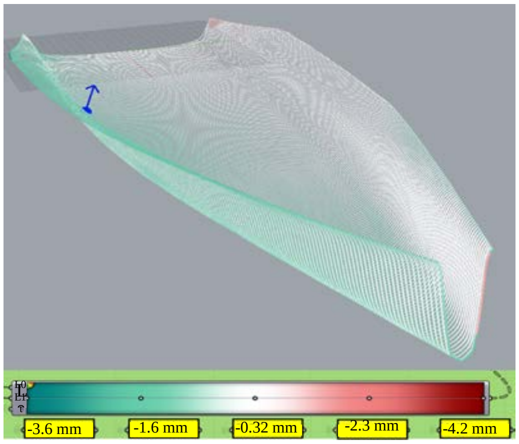

Fig. 10: Map of the deviation values of the real hull shape with regard to the CAD Model

This procedure has allowed to calculate the deviations of the photogrammetric model compared with the project one; the variations are of a few millimeters as shown in Fig. 10.

CONCLUSION

Two new algorithms to analyze surfaces coming from reverse engineering studies have been developed. A free open source graphical generative algorithm editor has been used. The first procedure allows evaluating the quality of a rebuilt surface by comparing it with the acquired data. The second one, instead, allows to compare the acquired surface with the nominal CAD Model to measure the deformation of the real model. Both the algorithm have been tested using a small sailing yacht as case study. The obtained results demonstrate that the developed procedure is very efficient and able to give detailed information on the deviation values between two compared surfaces. The proposed algorithms could be also used with data coming from different reverse engineering systems (laser scanner, DIC, Moire fringes based, etc.) so allowing a very large field of use.

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