Underwater photogrammetry for 3d modeling of floating objects: the case study of a 19-foot motor boat

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ABSTRACT: 3D modeling of floating or semi-submerged objects is a challenging and attractive task for the marine industry especially if the manufacturing of components that have to be replaced or repaired after a damage is necessary or the ship itself has to be converted. Up to now the 3D reverse engineering of ships has required docking operations to carry out a geodetic or photogrammetric survey with high costs for shipowners. In this paper an innovative 3D acquisition method for digital recording of floating objects is presented. The method is based on digital photogrammetry both underwater and terrestrial. Preliminary tests are presented for the case study of a 19-foot motor boat. Two surveys of the boat in floating conditions are carried out and then joined by means of special rigid orientation devices built ad hoc.

1 INTRODUCTION

Nowadays the knowledge and digital representation of boat hull and appendages is a fundamental issue from the naval architect point of view. The 3D digital model is the starting point of the iterative design process (well known as "design spiral") that is followed during the practical design of a new craft. However, retrieving the actual shape of an existing vessel or its part can be also necessary when no product information exists as in the case of digital documentation of maritime heritage (Menna et al 2011, Wiggenhagen et al 2004), (Kentley et al. 2007b) or when such information is considered unreliable because of deformation and/or damages occurred over time (Koelman 2010), (Menna et al., 2009), (Menna & Troisi 2007), (Goldan & Kroon 2003). For this purpose, a reverse engineering procedure is needed to reconstruct the shape, dimension, and semantic information of the surveyed object. The measurement technique represents the basis of the reverse engineering workflow and the choice of the survey method depends on several factors (object location, object size, required accuracy, kind of analysis to be performed, etc.) (Remondino & El Hakim 2006) (Remondino et al 2005), which have to be clearly defined a priori.

For retrieving digital models of marine vehicles or floating objects in general, high precision measurements are usually performed with the object beached or docked. Such operations are highly costly for shipowners as the unit must be set in out of service. Other practical difficulties may arise due to the setting (dry or floating docks) where the survey has to be conducted, often characterized by restricted spaces, disadvantageous environment conditions (e.g., water, wetness, saltiness), etc.. In previous works (Menna et al., 2010) (Menna et al., 2009) (Ackermann et al 2008) (Menna & Troisi 2007), the authors showed that digital photogrammetry is suitable for shipbuilding ashore applications. The photogrammetric technique has been successfully employed for obtaining dense and accurate 3D models of free form surfaces from digital images in accurate, flexible and economical way. Applications of underwater photogrammetry have been also presented; the technique has been proved useful for mapping and retrieving the shape and geometry of objects completely submerged. In particular many published papers are focused on archeological site surveys (Drap et al 2007), (Canciani et al 2003) or monitoring of marine fauna populations (Shortis et al 2007). In the knowledge of the authors up to know there are no scientific publications about the reverse modeling of floating or semi-submerged objects and structures. The measurement of an object below and above the sea level is of great interest for the marine sector especially for manufacturing the replacement elements needed for damage repair or conversion of ships. Usually, the repair of damaged ship hulls starts with a visual inspection for establishing the nature and extent of the damage below and above waterline. This is important for determining the need and the possibility of carrying out repairs in situ, the work method, and the cost of repair for the insurance (Goldan & Kroon 2003). The advantage of recording the shape of a floating or partially submerged structure could be an attractive solution for speeding and reducing the costs of survey and repair operations.

In this contribution, an innovative methodology is presented: a consumer-grade digital camera was employed for retrieving the 3D digital model of a 19-foot pleasure motor boat in floating conditions. By mounting the camera in a low-cost water proof housing, the entire hull (both the parts below and above the sea level) was surveyed. The survey is divided in two photogrammetric surveys: (i) above ("dry") and (ii) below (underwater) the sea level. The two surveys are then joined together by means of ad-hoc orientation devices (which use photogrammetric circular targets). The paper covers the whole workflow of the photogrammetric approach, starting from the camera calibration up to the assessment of the obtainable accuracy and the realization of the digital model suitable for naval architecture purposes. Interesting potentialities of the proposed method are discussed and motivated.

2 DIGITAL PHOTOGRAMMETRY FOR SHIPBUILDING APPLICATIONS

Photogrammetry is a flexible and accurate three-dimensional (3D) measurement technique based on photographs of an object taken from different points of view. Its success became technically and economically evident in the mid 1980s based on analogue large format cameras. Especially for large volume objects with a high number of object points to be measured, close range photogrammetry could exceed the performance of theodolite systems and thus became a standard method for complex 3D measurement tasks (Luhmann 2010).

Once a camera has been calibrated (i.e. geometric parameters of the camera and lens distorsions are known) (Gruen & Beyerv2001) (Granshaw 1980) the photogrammetric process translates into marking some corresponding object points on the images to determine camera positions and orientations (Exterior Orientation) as well as 3D point coordinates. The recognition of the same object point on two or more images (image correspondences) requires the object surface to have enough texture information (such as natural points and/or edges, etc.). If no features are visible on the images, then artificial targets must be positioned and/or synthetic patterns must be projected or painted on the surface object (Luhmann 2010) (Menna & Troisi 2010) (Menna et al 2009) (Ackermann et al. 2008). For some applications, i.e. for high automation and accuracy purposes, circular coded targets should be positioned on the object to automatically recognize image correspondences.

Nowadays digital photogrammetry is capable of offering high precision and accuracy levels. The precision of image point measurement can be as high as 1/50 of a pixel, yielding typical measurement precision on the object even better than 1:100000 with respect to the largest object dimension. That corresponds to 0.1 mm for an object of 10 meters (Luhmann 2010).

Over the last few years, the shipbuilding field has seen remarkable experimentation in reverse modeling and re-engineering of ship hulls. In (Koelman 2010) (Goldan & Kroon 2003) CAD applications of photogrammetry for ship repair industry are presented. In (Menna & Troisi, 2010) different low cost techniques, both active and passive, were tested and compared for the 3D reverse engineering of a small screw propeller. In (Menna et al, 2009) close range photogrammetry was used for the digital record of a 24-meter ship hull with 1:40000 relative precision and performing several kind of inspections on its appendages and propellers. In (Ackermann et al 2008) and (Menna and Troisi 2007) the authors showed the potentialities of image matching algorithms in delivering high density point clouds useful for modeling free form surfaces such as those of towing tank models or sailing boats.

3 DIGITAL PHOTOGRAMMETRY FOR 3D MODELING OF UNDERWATER ENVIRONMENTS

The use of photographs as a mean for visual inspection and analysis of objects located below the sea level has a long history. First underwater photographs taken with primitive camera housings date back to the 1850s, using glass plate as a medium. To see first underwater photogrammetric applications it is necessary to wait until the 1960s when film cameras and television cameras were used in stereo pair configuration (the minimum for 3D measurements) as metrology technique for repairs on marine equipment, archeological site mapping, monitoring of fauna populations and shipwreck surveys (Shortis et al 2007). The advent of digital era has led to many practical and technical advantages in underwater photogrammetry. Low cost consumer digital cameras mounted in a waterproof housing can deliver very precise measurement whose absolute accuracy is limited only by the turbidity of the water that drastically reduces the overall image contrast, hence the accuracy in image point marking. The accuracy of a photogrammetric system is always related to the calibration of the camera. Utilizing cameras for underwater photogrammetry poses some non trivial modeling problems due to refraction effect and extension of the imaging system into a unit of both camera and protecting housing device.

Two different mathematical models have been proposed for underwater photogrammetry (Telem & Filin 2010) (Shortis et al. 2007):

1 rigorous geometric interpretation of light propagation in multimedia (camera housing-water) also known as *ray tracing* approach (Li et al. 1997);

2. the refractive effect of the different interfaces is absorbed by the camera calibration parameters as if the camera was normally calibrated for terrestrial applications (Harvey & Shortis 1998).

The advantage of the first approach is that the camera can be calibrated out of the water but requires the refractive indices of the air-glass and glass-water interfaces to be assumed or directly measured. Small changes in pressure, temperature and salinity can decrease the accuracy and cannot be eliminated. The second approach has the disadvantage that cameras need to be calibrated underwater. For underwater photogrammetric systems mounted on Remotely Operating Vehicles (ROV) the difficulty becomes obvious especially if surveys have to be carried out at different depths. Shortis et al (2007) overcame the problem using a special laser array for the calibration of an underwater stereo video system on the field.

In this paper the approach number two for modeling refractive effects of multimedia interfaces has been used.

4 FULL PHOTOGRAMMETRIC SURVEY OF SEMI-SUBMERGED OBJECTS: A CASE STUDY

The case study here presented is part of a wider project called OptiMMA (Optical Metrology for Maritime Applications) involving the Laboratory of Topography and Photogrammetry (LTF) of Parthenope University and the 3DOM optical metrology unit of Bruno Kessler Foundation (FBK). The project is an interdisciplinary work based on optical metrology and 3D reverse engineering techniques in the maritime field for the support of shipbuilding firms, naval architects and designers.

A 19-foot fiberglass boat (Fig 1) was chosen for testing a new methodology for 3D reverse modeling of floating objects. The study aims to reveal practical and technical issues involved in measuring semi-submerged objects and structures of large size for which dry-docking is usually difficult and expensive. The methodology here presented can be easily extended to larger size boats.

Figure 1. The boat used for testing the reverse engineering technique.

4.1 *Calibration*

The equipment used for the photogrammetric survey consisted in a 7 Mpx CANON A620 (pixel size 2.3μm) consumer grade digital camera mounted in a dedicated waterproof camera housing (Fig. 2).

Figure 2. Consumer digital camera (left) and waterproof housing (right) used for the photogrammetric survey of the boat

A volumetric rigid frame made of aluminum was specifically built for underwater calibrations (Fig 3 - up). It consists of a cross shape with four arms holding four triangular plates. 128 photogrammetric circular coded targets are attached on the frame for high accuracy automatic measurements. The frame measures approximately 530 mm x 530 mm x 200 mm.

Two 1000 mm long aluminum scale bars were also built for scaling photogrammetric underwater measurements. The circular targets of the frame and the scale bars were accurately measured by means of photogrammetric and theodolite measurements in laboratory (Fig. 3 - down). The average theoretical precision of target coordinates are σ_X=0.005 mm, σ_Y=0.006 mm and σ_Z=0.009 mm which corresponds to an overall relative precision of 1:100000.

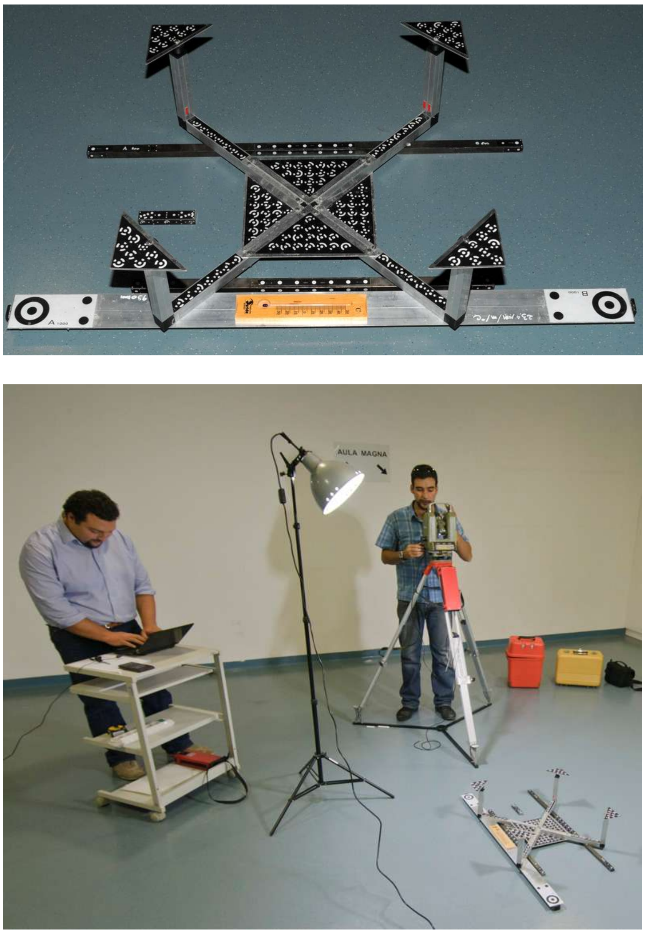
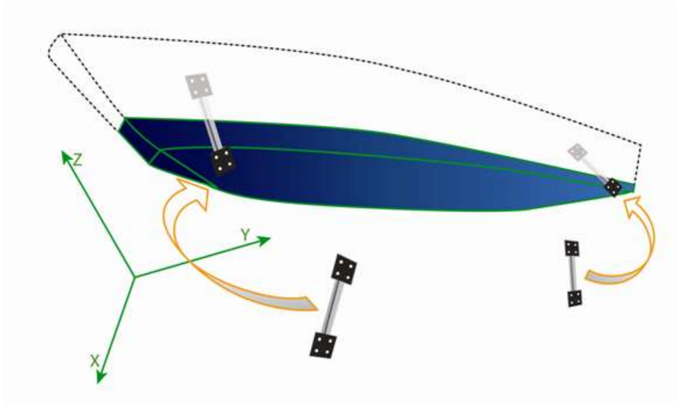


Figure 3. Calibration frame and scale bar (up) arranged for laboratory measurement (down).

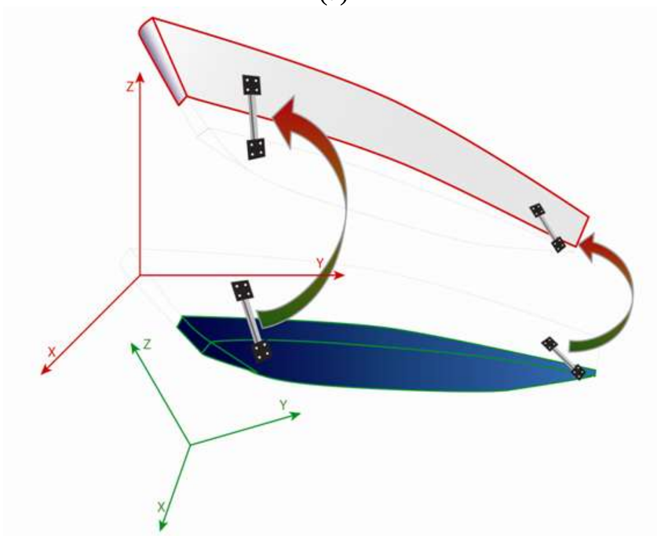
The method for 3D modeling of semi-submerged objects herein presented can be summarized as a two-step photogrammetric survey (underwater and above the waterline) followed by a roto-translation of the two separated surveys in a unique reference frame. Four rigid orientation devices (OD) were specifically designed for the photogrammetric survey of floating objects. They consists of an aluminum bar (ca 600 mm long) with two thick Plexiglas plates attached to the extremities (Fig. 4). Each plate has four circular coded targets. The device is intended to be fixed on the surveyed object staying an half (one of the two plates) underwater and the other half above the sea level. The 8 target coordinates for each of the four orientation devices were measured in laboratory with photogrammetric measurements.

Once calibrated, one orientation device allows to join the two surveys executed underwater and above the waterline respectively. In order to guarantee a better solution during the computation of roto-translation parameters a good geometric distribution and redundancy of the orientation devices onto the object is necessary.

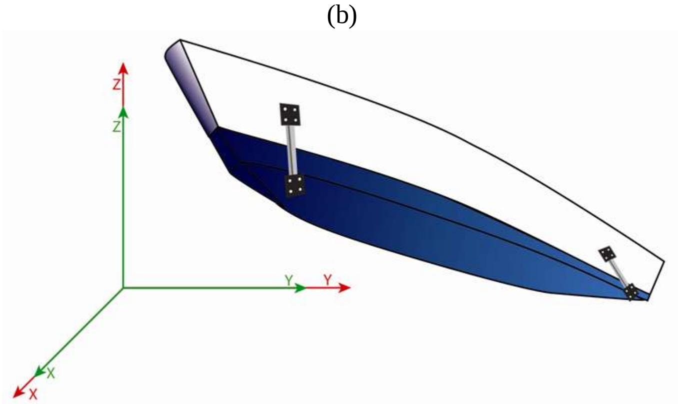
The way each OD allows to join the two surveys can be explained as follows: (i) the 4 coded targets on each plate of the OD were previously measured in laboratory (the relative position between the two plates is accurately known); (ii) the coordinates of one plate are measured for example in the underwater survey (figure 4a), (iii) by means of the measured 4 coded targets, the OD is aligned (roto-translated) in the underwater reference system, then the coordinates of the plate above the sea level are also known with respect to the underwater reference frame; (iv) the coordinates of the emerged plate, known in the underwater system, are used for aligning the survey above the waterline to the underwater survey (figure 4b,c).



(a)



(b)



(c)

Figure 4 – Schematic procedure of the alignment of the two separate surveys above and below the waterline.

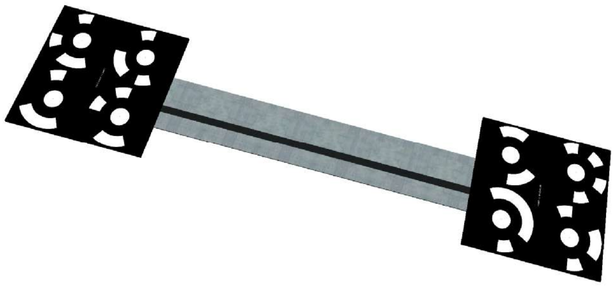


Figure 5. CAD model of one of the 4 rigid orientation devices.

In order to investigate the differences in camera calibration parameters between "dry" and underwater calibrations the Canon A620 was mounted in the waterproof camera housing and calibrated in "dry" conditions in laboratory using the calibration frame in figure 3. Focal length was set to the widest available (having the camera a zoom lens), corresponding to a nominal principal distance of 7.3 mm. The network geometry consisted of 15 convergent poses (average angle between intersecting angles ca 75 degrees) of the calibration frame taken at an average distance of 1 meter. The self calibration procedures in free network solution exposed in (Gruen & Beyerv2001) (Granshaw 1980) were used. PhotoModeler and Australis software were used to compute the interior and exterior orientation parameters together with the additional lens distortion parameters to model any systematic error. As described in (Wackrow et al. 2007) for the terrestrial case, it is noteworthy that some additional parameters such as decentring distortion parameters (also known as tangential distortions) are not statistically significant for most consumer grade digital cameras. Therefore, ignoring the computation of decentring distortion parameters has no practical effects in terms of reduction of object coordinate precision. On the other hand, in the case of underwater calibrations of video-cameras, (Harvey & Shortis 1998) underline the importance of decentering distortion parameters in absorbing systematic errors whose behaviour cannot be modelled by collinearity equation model. During the experimentation herein proposed, two sets of calibration parameters were computed (with and without decentring distortion parameters). As expressed by (Harvey & Shortis 1998), changes in pressure and temperature and even more the handling of the camera itself produce instability in the camera calibration parameters. For investigating the effect of camera handling during the underwater survey as well as the effects caused by change of pressure and temperature (from the waterline down to 5 meters), two different calibrations were executed at temporal distance of circa 1 hour: (i) shallow water (Fig. 6-left), (ii) at a depth of 4m (Fig 6-right). The two different depths are the minimum and maximum depths the camera is planned to be used during the underwater survey of the test-boat. For each calibration an average of 16 images were taken with convergent poses (average intersecting angle of ca 85 degrees) at a distance of 1.5 m from the calibration frame.

In table 1, "dry" and underwater calibration parameters are reported. For each calibration two versions (V1 and V2) are listed: with and without tangential distortion parameters (P1, P2 parameters). For the underwater survey of the boat, calibration parameters without tangential distortions (V2) were used since high statistical correlations (over 97%) were found between principal point position and tangential distortions. Furthermore, some calibration parameters for version V1 such as the principal point position and focal length were not consistent between the two calibrations in shallow water and at 4 m (Table 1). The average ratio between the focal lengths computed in underwater and dry calibrations is equal to 1.342 that corresponds to the refractive index of sea water at 26°C and salinity of 38 g/kg. To investigate the accuracy of the digital camera used in these experiments in underwater environment, the 3D coordinates of the calibration frame measured in laboratory were compared to those obtained from the underwater self calibration bundle adjustment. The root mean square error of 3D coordinates measured in underwater calibrations were respectively σ_X=0.045 mm, σ_Y=0.024 mm, σ_Z=0.090 mm.

Table 1. Calibration parameters of the camera used for the survey of the boat. Both dry and underwater calibrations are reported.

Camera calibration Name	DRY_V1	DRY_V2	UW-4m_V1	UW-4m_V2	UW-0.5m_V1	UW-0.5m_V2
Focal length [mm]	7.3175	7.311	9.8299	9.8197	9.8084	9.8113
Principal Point x0 [mm]	-0.0635	-0.066	-0.0344	-0.0606	-0.0807	-0.0632
Principal Point y0 [mm]	-0.051	-0.0648	-0.0173	-0.0478	-0.0544	-0.0609
k1	3.86E-03	3.81E-03	-2.77E-04	-3.12E-04	-3.01E-04	-2.97E-04
k2	-7.47E-05	-7.08E-05	-7.80E-05	-7.45E-05	-7.27E-05	-7.34E-05
k3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
P1	-1.25E-05	0.00E+00	-1.25E-04	0.00E+00	8.72E-05	0.00E+00
P2	-6.50E-05	0.00E+00	-1.48E-04	0.00E+00	-3.12E-05	0.00E+00

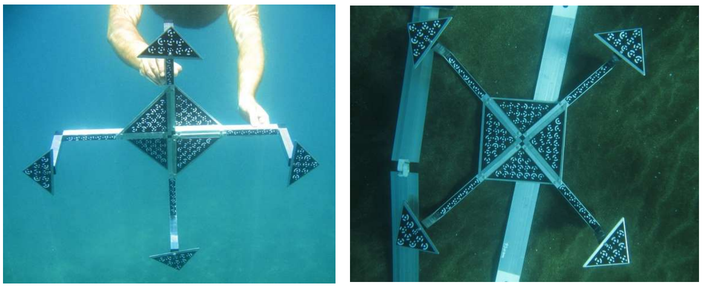


Figure 6. Two images used for the underwater calibrations of the Canon A620 in shallow water (left) and at a depth of 4m (right) respectively.

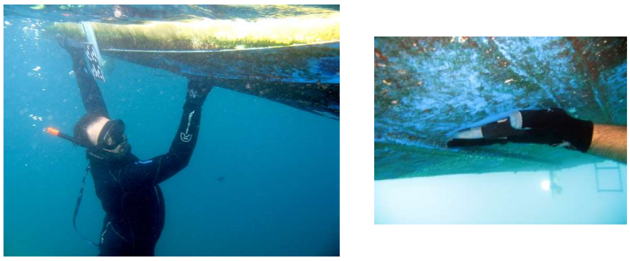


Figure 8. Sticking operations of circular coded targets on the hull of the boat..

In figure 7 radial distortion profiles for versions V2 of Table 1 are plotted for dry (up) and underwater (down) calibrations. For underwater calibrations only one graph is shown since differences between the two calibrations can not be appreciated in the figure.

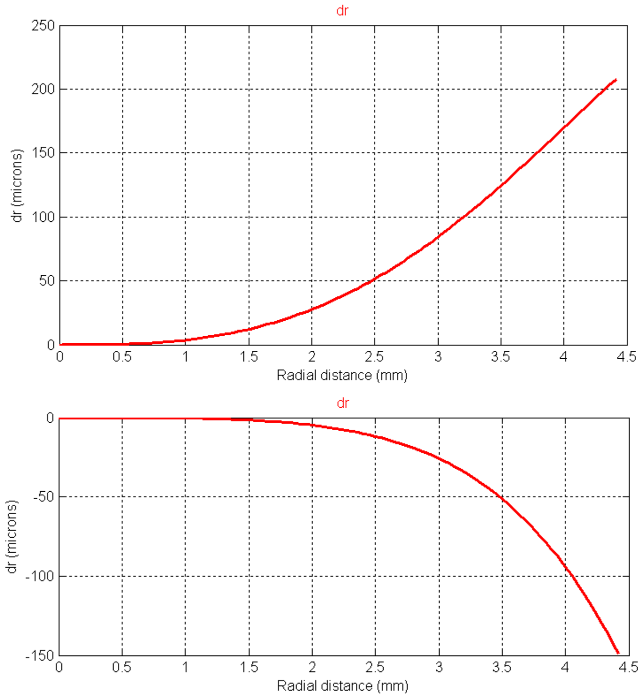


Figure 7. Radial distortion profiles for "dry" calibration (up) and underwater calibrations (down).

4.2 *Survey*

The 19-foot boat "Mano 19" was anchored in 6 meters of water along the coast of Procida island in the gulf of Naples. About 50 photogrammetric circular coded targets were stuck both above and below the waterline (Figure 8) and some strips of circular targets were attached along the keel and the stem to determine the boat centreplane. Two aluminum scale bars were attached one below and the other above the waterline.

The four orientation devices were placed aft and fore, symmetrically on the two sides of the boat. Each orientation device has respectively one plate below and above the waterline (Figure 9). Since the boat is made of fiberglass, targets and orientation devices were attached with a special water resistant double-sided tape. The targeting operations required circa 1 hour.

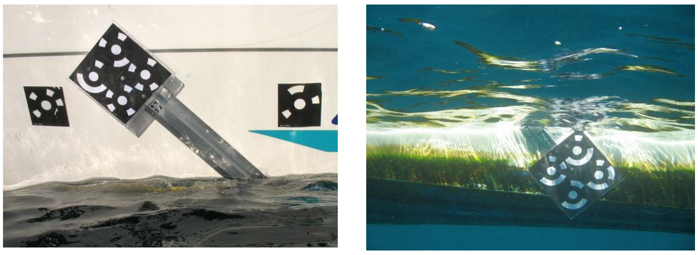


Figure 9. Two photographs of a same orientation device above and below the waterline respectively.

The photogrammetric survey consisted of two set of images of the boat taken underwater and above the waterline trying to keep a good network geometry of camera stations (Fraser 1996). The underwater photogrammetric modeling of boats can be very troublesome since to survey the bottom of the hull, photographs have to be taken pointing the camera up toward the sea surface. In this condition the influence of the dispersion effects of water, the presence of suspension, flare and other optical aberrations reduce sensibly the accuracy of point marking operations on the digital images, hence the precision of 3D point coordinates.

The two sets of images were oriented using PhotoModeler software in two separate projects using coded targets to automate the orientation stage. Table 2 summarizes the main characteristics and results of the two photogrammetric surveys.

Table 2. Main characteristics and results of the survey.

	Underwater	Above
N° of images	50	40
Average distance [m]	2.5	2.5
Pixel footprint [mm]	0.6	0.8
Average intersecting angle [degrees]	61	67
Theoretical precision σ_X [mm]	0.49	0.41
Theoretical precision σ_Y [mm]	0.57	0.26
Theoretical precision σ_Z [mm]	0.56	0.17
Relative precision	1:6500	1:12000

To bring the two surveys in a unique reference frame the four orientation devices were used. The procedure consisted in the following steps. First, similarity transformation parameters are computed to bring each of the four OD in the underwater surveys. In this way the 3D coordinates of the 4 points on the plates above the waterline become known in the reference frame of the underwater survey. The operation is repeated for the photogrammetric survey above the waterline hence the 3D coordinates of the 4 points on the plates underwater are known in the reference frame of the "dry" survey. After this operation, the two separate surveys have 32 common points that can be used to compute the similarity transformation parameters to bring the surveys in a unique reference frame. After alignment of the two surveys the standard deviation of residuals on the plates of the orientation devices were respectively σ_X=1.1 mm, σ_Y=2.1 mm, σ_Z=0.9 mm. From (Figure 9) it is visible that maximum residual exceeds 4 mm (green bars). This behavior is probably due to small movements of the orientation devices caused by movements of the boat. During the survey operation the transit of many local ferries caused waves and frequent roll movements of the boat then, likely, the plates of the orientation devices worked as oars into the water. The roll movement can explain the maximum residuals in y direction (starboard-port axis).

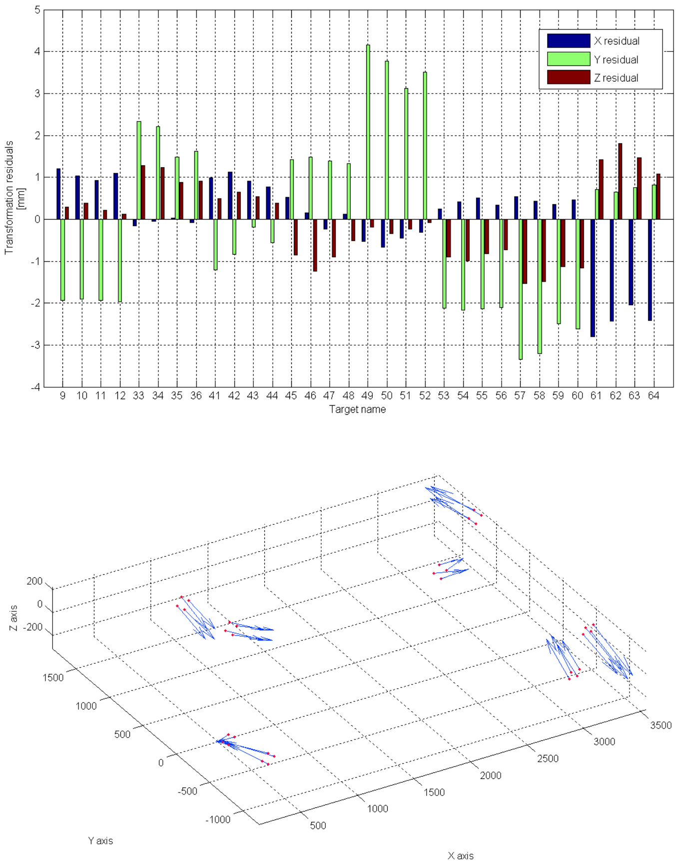


Figure 9. Residuals of the similarity transformation on the targets of the orientation devices.

After the joining of the two separate photogrammetric projects, a global bundle adjustment was performed and many manual points, edges and lines were measured on the images to obtain features of interest for the 3D modeling of the boat (Figure 10)

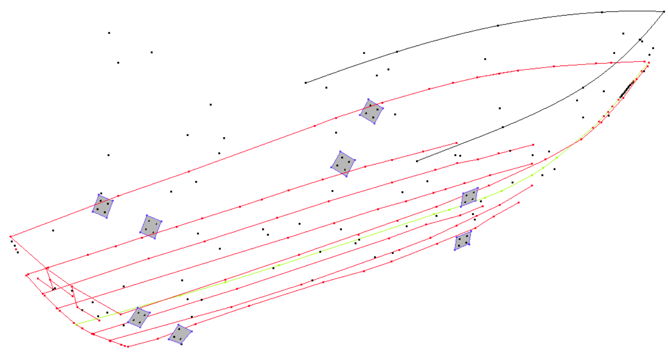


Figure 10. Feature lines and points measured in Photomodeler after the union of the two photogrammetric surveys.

4.3 *3D Modeling*

Feature lines and points were imported in ***DELFT-ship*** (www.delftship.net) a free hull modeler software that includes hydrostatic calculations.

The 3D photogrammetric data were used as reference for modeling a symmetrical hull composed by subdivision surfaces (Figure 11).

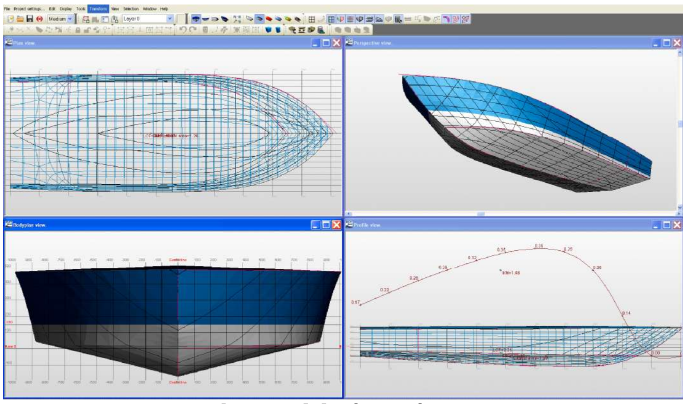


Figure 11. DELFT-ship model of *Manò 19.*

5 CONCLUSIONS

In this contribution a new method for 3D modeling of floating objects has been presented in the case of a 19-foot fiberglass boat. The significance of the method is due to the fact that it does not require the ship to be docked.

Two photogrammetric surveys, underwater and above the sea level respectively were performed with the boat in floating conditions. The two surveys were then joined together by means of ad-hoc orientation devices (calibrated in laboratory), with photogrammetric circular targets. A consumer-grade low cost digital camera mounted in a waterproof housing was employed for retrieving the 3D digital model by means of digital photogrammetry. The whole workflow of dry and underwater camera calibrations, survey operations and 3D modeling of the boat have been analyzed. The results of the experiments are encouraging since sub-millimeter precision was obtained for the two separate photogrammetric surveys and 1-2 millimeter accuracy was obtained from the alignment of the two surveys in a unique reference frame. The larger residuals obtained along the *y* axis (Figure 9) have shown some instability troubles of the orientation devices probably due to the double-sided tape used to attach them on the hull. It is noteworthy that the characteristics of the boat surveyed in the experiment were really challenging for the tested methodology. In fact, for larger ships made of steel, orientation devices can be attached by means of strong magnets that can assure much more stability. Furthermore, the movements of larger ships are in general smaller than the tested boat.

The case study of the 19-foot boat has been especially interesting for testing the proposed methodology. In fact, dry-docking of vessels of this size is usually easy and inexpensive. In the future, the method will be applied for the reverse engineering of large size vessels.

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