Digital Photogrammetry For High Precision 3D Measurements In Shipbuilding Field

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Abstract

Nowadays precise measurements of hulls, propellers and other appendages are an issue still open in naval architecture field. The complex shapes, that are often involved, require dense and accurate measurements.

This paper shows the results achieved by applying digital photogrammetry techniques for 3D objects modelling. The whole flowchart, from camera calibration and image acquisition to the application of reverse engineering techniques, was examined on both screw-propeller and hull towing tank models. A critical and detailed analysis of processes involved has been carried out together with the discussion on the benefits of the proposed technique to full scale objects.

Keywords:

Digital Photogrammetry, Image Matching, Hull, Screw-Propeller, 3D Modelling

1 INTRODUCTION

Nowadays three dimensional (3D) models are becoming a key topic in many fields owing to new technologies and software that have extended their potentialities. Medicine, engineering, cultural heritage documentation represent just a few areas of interest among a wider spectrum of applications. Each of these disciplines needs measurements characterized by specific aspects such as high accuracy and reliability for engineering 3D models or a good arrangement between accuracy and a pleasant visualisation for cultural heritage documentation.

3D models are digital representations of the real world generated by means of metric knowledge of the object’s shape. In many cases such information can be derived directly from the original design for engineering application, from a map in cartography, etc.. If no 3D information are available from any source, a survey of the object is requested.

Several parameters characterize survey techniques such as accuracy, which is considered the most important one, but also other not negligible variables like costs, reliability and flexibility which are not negligible details as well as the time required for developing the entire process.

Currently 3D models are generated starting from a point cloud measured by means of active sensors like laser scanners or fringe projectors that are, in any case, still very expensive instruments. These new technologies allow for extremely fast surveys since they are capable of measuring millions of points in a few minutes but, at the same time, they need a very onerous editing stage in order to process data which, in many cases, also lack semantic information. Indeed, automatic instruments are not equipped by a precision collimation system to restrict the survey at only a few elements of interest. A great number of technologies are involved in metrology, starting from simple direct contact methods like the tape rule to the most expensive laser trackers and coordinate measurement machines (CMM) [1]. Owing to the wide range of applications and to the complex degree of variability, there is no unique technique that can be considered best in terms of accuracy, reliability and flexibility. For example a simple tape rule may be suitable for measuring a small object with easy shapes when the required accuracy is some millimetres whereas it is absolutely inappropriate for a complex shape with double bend continually variable such as a boat hull. The best solution is obviously the one specifically studied for a class of objects, similar for shape and size.

Within this panorama, a valid alternative to the other techniques is photogrammetry due to its flexibility which allows for high accuracy measurements in a wide variety of applications with minimum costs.

Measurements in naval architecture and shipbuilding fields are an example of the above-mentioned applications where different accuracy levels for different object sizes are required.

In this paper, two examples of close range photogrammetric surveys in naval architecture field are presented. The benefits of photogrammetric systems are proved on objects characterized by different sizes: a 4.6 m overall hull model (typical size for towing tank resistance tests [2]) and a scale screw-propeller model with a 180 mm diameter (a stock screw-propeller for towing tank self propulsion tests). Low cost instrumentation was used to carry out the surveys.

Both laboratory measurements and original lines drawings were used for comparison with the 3D image-based models in order to assess both reliability and accuracy achievable with the proposed photogrammetric method.

2 PHOTOGRAMMETRIC PROCESS

Photogrammetry is an old technique, used since the second half of the nineteenth century especially in cartography and architecture. Very similar to the theodolites survey techniques, since it is based on the intersection between two or more optical rays, photogrammetry was bound to be used only by experts with very expensive instrumentation.

Thanks to the coming of digital era and new developments in the informatics (both hardware and software), photogrammetry has become a powerful, cheap and easy to use methodology. Digital cameras, equipped with high resolution frame sensors, are getting very common and inexpensive if compared to the old metric and semi-metric film cameras. Critical and expensive stages, like camera calibration by means of special instrumentation in dedicated laboratories, are now avoidable for close range photogrammetry. Nevertheless, unlike topometrical active sensors, photogrammetry does not allow for retrieving directly 3D point clouds of the objects and requires some fundamental steps that will be shown and described in this paragraph.

2.1 Camera Calibration

A photograph can be regarded as a central perspective often associated to a simple device called "pinhole camera". Within this geometric model, three elements are sufficient to describe entirely the perspective: focal distance and the intersection point coordinates of the optical axes with the image plane (interior orientation). Nevertheless such a model is far from the real one due to the presence of lens that causes optical distortions.

The camera calibration procedure consists exactly in recovering this perspective elements, so called interior orientation, together with radial and decentring lens distortion parameters.

Nowadays, thanks to the coming of digital sensors, such procedure can be realized analytically in a few minutes by taking some photographs (with the same camera settings) of a particular test-field (Figure 1) and processing them with specific freeware or commercial software.

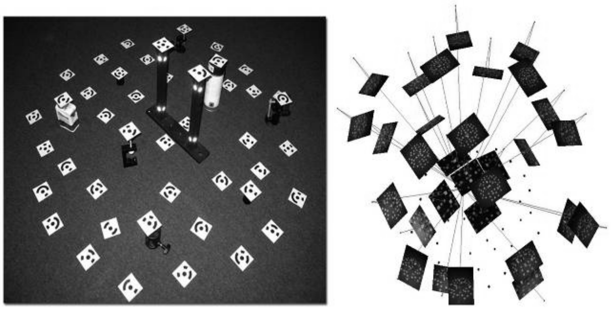


Figure 1: Calibration test field.

This camera calibration procedure is called "self calibration" to distinguish it from the laboratory procedure carried out with optical "multi-collimators". The self calibration procedure is generally performed as the first step of photogrammetric flowchart, even though it is possible in many cases [3] to recover camera calibration parameters using the same object to survey as a test field.

2.2 Image acquisition

Photogrammetry is able to get 3D data of an object from images; it is based on the principle of the intersection between two or more (redundancy) straight lines. Within the perspective model, object point, perspective centre and image point lie on the same straight line (collinearity straight line).

The image acquisition stage consists in taking photographs of the object from different view positions, ensuring good intersection between collinearity straight lines.

Since in photogrammetry recognition of the same object point on two or more images is required, it is necessary that the object has enough texture information. The photogrammetric process is closely related to mark some object points on the images to determine both camera positions and orientations (exterior orientation) as well as 3D points coordinates. Such points can be object features (intersection of edges, natural points, etc.) or artificial targets previously placed on the object.

Image acquisition is probably the most important stage in the photogrammetric flowchart since results are strongly dependent from the characteristics of the images.

Among other parameters, accuracy is often considered as the main one in a survey; in photogrammetry it strictly depends on the image scale (focal lens and camera distance from the object), camera characteristics (pixel size, resolution) and image stations configuration (convergent or parallel axes and image redundancy).

If a stereo vision of the object is required, photographs have to be taken with optical axes not far from the parallelism; generally convergent optical axes of cameras ensure good intersection but may be not useful for stereo vision and image-matching processing with many commercial software [4]. In order to scale the generated 3D model, at least a distance between two marked object points or a distance between two camera stations must be known, and therefore measured before image acquisition. In some cases the use of photogrammetric coded targets can considerably improve, in terms of operation speed and accuracy, the exterior orientation stage which happens almost automatically.

2.3 Exterior orientation

Interior orientation establishes the bundle of rays (collinearity straight lines). Exterior orientation establishes the position and orientation of the bundle of rays with respect to the object space coordinate system.

Each bundle requires six independent parameters: three for position and three for orientation. These parameters can be calculated either through the knowledge of some 3D object points (at least three) coordinates (single image orienting, resection) or by marking same object points (at least five) on two or more images (image pairs orienting, relative orientation). Once that approximated values for exterior orientation parameters are computed, a least square evaluation by means of a bundle adjustment process (multi image orienting) is performed in order to improve the accuracy.

Experimentations in photogrammetric communities [5] have shown that:

- the accuracy of a network of camera stations increases with the increase of the base to depth ratio (B/D, where B is approximately the distance between two camera stations and D is the distance to the object) and the use of convergent images rather than images with parallel optical axes;
- the accuracy improves significantly with the number of images in which a point appears;
- the accuracy increases with the number of measured points per image. However, the increase is not significant if the geometric configuration is strong and the measured points are well defined (like targets) and well distributed in the image;
- the accuracy is influenced by the image resolution (number of pixels) of the computed object coordinates: on natural features, the accuracy improves significantly with image resolution, while the improvement is less significant on well-defined targets.

Object coordinates and image coordinates are related by the "collinearity equations":

$$\begin{bmatrix} x - x_o \\ y - y_o \\ -f \end{bmatrix} = \lambda \mathbf{R} \begin{bmatrix} X - X_C \\ Y - Y_C \\ Z - Z_C \end{bmatrix} \quad (1)$$

where:

- x_o, y_o, f are interior orientation parameters;
- X_C, Y_C, Z_C are camera station coordinates;
- $\mathbf{R}$ is the rotation matrix containing camera station angles;
- λ is the scale factor;
- x, y are the image coordinates;
- X, Y, Z are the object coordinates.

2.4 Plotting and point cloud generation stage

Once the exterior orientation parameters have been computed, 2D image points coordinates can be transformed into 3D object coordinates by means of collinearity equations.

Image-based modelling can be executed in manual, semi-automated or fully-automated way. In any case, the procedure consists in marking homologues image points in each image.

Manual measurements are characterized by high reliability and good precision (depending on the operator), but they are time consuming and suitable for low-definition 3D models. Fully-automated measurements are instead fast and precise but often not reliable because mismatches (outliers) in the search for homologues points can occur. Nevertheless for many tasks they are preferred to manual measurements because they supply for high density point clouds. The presence of possible outliers is checked and removed during the post processing stage by manual editing or automated filtering methods.

Fully-automated methods use image matching algorithms which consist in finding correspondence between primitives extracted from two or more images [4]. For full 3D objects (two or more opposite sides), a segmentation in simpler 2.5D surfaces is required [6]: this is due to some limitations of image matching algorithms implemented in commercial software, developed exclusively for aerial photogrammetry (2.5D surfaces for which at each *xy* of pair coordinates corresponds only one *z*).

In any case the accuracy achievable by photogrammetric methodologies in multi-image point measurements can be summarized by the empirical formula [7]:

$$\sigma_{XYZ} = \frac{q \cdot S}{\sqrt{k}} \sigma_{xy} \quad (2)$$

where:

- σ_{XYZ} is the accuracy of the computed object coordinates;
- σ_{xy} is the standard error of the image measurements;
- q is an empirical factor depending from the strength of the photogrammetric network geometry;
- S is the scale number (mean object distance/camera focal length);
- k is the number of images per station.

3 EXPERIMENTATION

Two study cases in the naval architecture field, different in terms of complexity and dimensions, have been tested in order to prove the potentialities of photogrammetry as a quick and precise survey technique.

The aim of this experimentation is to investigate the level of accuracy achievable with low cost amateur cameras in a field where active sensors and coordinate measurement machines (CMM) are, at present, the only instrumentations providing for the required precision (up to a tenth of millimetre for small objects such as screw-propeller models). International Towing Tank Conference (ITTC) community established tolerances that must be respected in building both screw-propeller and hull models used in towing tank tests [8].

In order to reach such precisions, image scale and camera network configurations, with both convergent and parallel axes, were carefully planned.

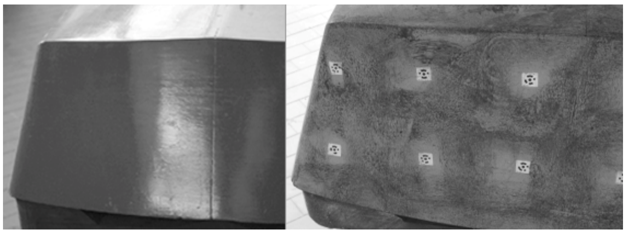
The following commercial software were used in the experimentation:

- Photomodeler® 5.2.3 (EOS Systems®): multi-image photogrammetric software with bundle adjustment method and self-calibration capability;
- Socet Set® 5.4 (BAE Systems®): digital workstation for aerial photogrammetry and NGATE (Next Generation Automated Terrain Extraction) module;
- Matlab® 7.1 (The MathWorks®): numerical computing environment and programming language used to execute similarity transformations, visualization of the Digital Surface Model (mainly texturing and VRML model generation);
- Geomagic Studio® 8 (Raindrop®): reverse engineering software used to edit, analyze and section the generated 3D model;
- Orthoengine® 10.1 (PCI Geomatics®): cartographic software used to rectify the digitalized body plan of the ship model.

3.1 Hull forms modelling

A complex hull geometry model (with double curvature surfaces, skeg and bulbous bow) was chosen among all the hull models available at DIN (Dipartimento di Ingegneria Navale of the University "Federico II" of Naples) towing tank.

The wooden hull model, approximately 4.6 m overall length, 0.8 m breadth and 0.4 m depth, was imaged by a NIKON D100 6 Mpx digital camera and a 35 mm fixed lens. The average scale number was planned to be 20 for the 400 images producing a pixel footprint of less than 0.2 mm.



(a) (b)

Figure 2: Surface of ship model before (a) and after (b) the treatment.

Problems of light reflections and texture homogeneity were solved by means of a reversible treatment of the surface with a solution of vinyl glue and washable tempera

(Figure 2) in order to allow homologues point recognition during the image matching process. Successively a set of coded targets (more than 500) were placed regularly on the surfaces in order to quick the orienting procedures.

Theoretical precision on the coordinates of each coded target, computed by the bundle adjustment procedure, had a maximum of 0.1 mm which means a relative accuracy of better than 1:46000.

The scaling of the model has been performed by placing a calibrated steel bar, 600 mm of length (Figure 3), in two different positions on the ship model (redundancy).

Figure 3: Calibrated steel bar used for scaling.

Once that the whole set of photographs was oriented, many reference notches, marked during the manufacture of the towing tank model, were determined photogrammetrically to define, with least square procedure, the lines drawing reference system (identified by the keel line, the longitudinal profile and the waterline plan).

Afterwards, six reference systems (one for each side of the model, one for the stern, and three for the bulbous bow) were defined to simplify in 2.5D surfaces the whole hull; the same number of point clouds were measured by means of image matching processes, performed on a regular grid of 2 mm. Each point cloud measured in its own reference system was registered in the body plan reference system by means of a procrustean method implemented in Matlab® environment.

The successive stage of editing and interpolation was controlled in order to preserve the theoretical planned accuracy (better than 1 mm). Such accuracy is fully within the manufacturing tolerances established by ITTC for towing tanks models (1 mm for depth and breadth and for length within ± 0.05% of total length) [8]; a polygonal mesh surface was generated with the points cloud and sectioned with planes parallels to the reference ones (Figure 4).

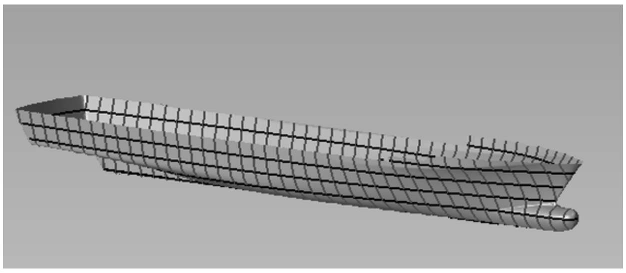


Figure 4: Main waterlines and stations on the photogrammetric model.

The obtained intersection lines can be directly compared with the 2D lines (stations, waterlines and buttocks) reported on the lines drawing. Due to the availability of the body plane only in papery format, a digitalization was performed; the successive rectification was necessary to correct distortions produced by both variations of the papery body plan (environmental conditions like humidity and temperature changes) and digitalization process itself.

The comparisons with the model body plan, revealed a discrepancy for the stations offsets less than 3 mm. This difference could be principally caused by physical distortions of the wooden model that is older than 20 years and therefore it might be deformed by environmental conditions.

A symmetry inspection between left and right side of the model was also performed: the right part of the model was compared with the mirrored left one (with respect to the longitudinal centreplane). Figures 5 and 6 reveal the presence of asymmetry having the modal value around 0 mm and a significant maximum localized around +2 mm.

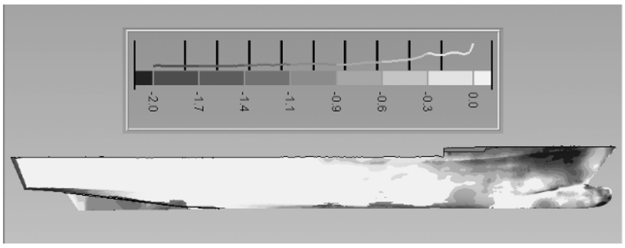


Figure 5: Asymmetry analysis (negative values).

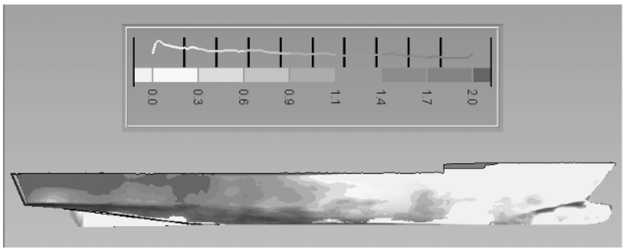


Figure 6: Asymmetry analysis (positive values).

The photogrammetric model can be exported in standard 3D format files (igs, wrl, 3ds, etc.) exploitable for further type of analysis such as hydrodynamic and hydrostatic ones, very common in naval architecture field.

3.2 Screw propeller modelling

The well known geometry screw-propeller model B3-50, belonging to the B-Wageningen screw series, was chosen for this experimentation.

The model, a bronze three right-handed blades with pitch and diameter of 180 mm, was surveyed with an amateur compact camera.

The great challenge for this experimentation was especially related to its dimension. An accuracy at least of 0.1 mm is established by the ITTC community for this class of objects [8], consequently a very large image scale was necessary to carry out the survey. With objects of reduced dimensions, small sensors have to be preferred to the bigger ones because of the depth of field. Indeed, at the same conditions (distance, image scale and aperture value), the depth of field is greater for small sensors. For this reason the survey was executed by acquiring 60 photographs with a Fujifilm S5600 5 Mpx digital camera and a 6.3 mm lens at a mean distance of 20 cm which leads to a scale number of 30 and a pixel footprint within 88 μm.

The camera was calibrated with macro settings on a small test field; as the used camera does not have a stable lens (any lock system is present) camera calibration and screw-propeller image acquisition were executed sequentially to keep unchanged the interior orientation parameters.

Figure 7: Camera stations configuration and blades profiles.

In order to minimize light reflections on the metallic surface, a homemade still-life set with diffused controlled lights was used and a greasepaint layer was applied too. A strong camera network (Figure 7) was planned to achieve the ITTC required accuracy [8].

Exterior orientation procedure was performed by using both coded target and natural points: despite the reduced depth of field there were not problems during automatic target recognition process. Residuals for the coded target were limited in a range 0.01 ÷ 0.02 mm; for the natural points maximum residual was 0.17 mm.

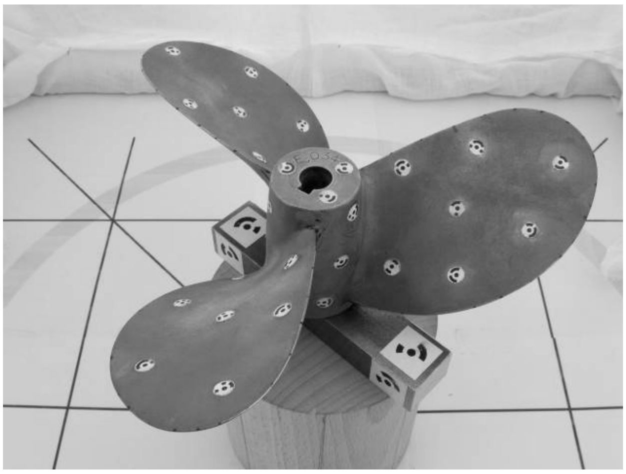


Figure 8: Screw-propeller and steel bar used for scaling.

Finally, scaling was executed by using a calibrated still bar of 100 mm (Figure 8).

In the same way of the ship hull model, a treatment of the surface was required before image acquisition stage. However, due to the more limited tolerances, no substances that could make thickness were used to create texture: only coloured dust chalk was used.

For the image matching process, nine reference systems were used, due to the particular geometry of the screw-propeller (three for the pressure faces of the blades, three for the back-suction faces and three for the propeller boss).

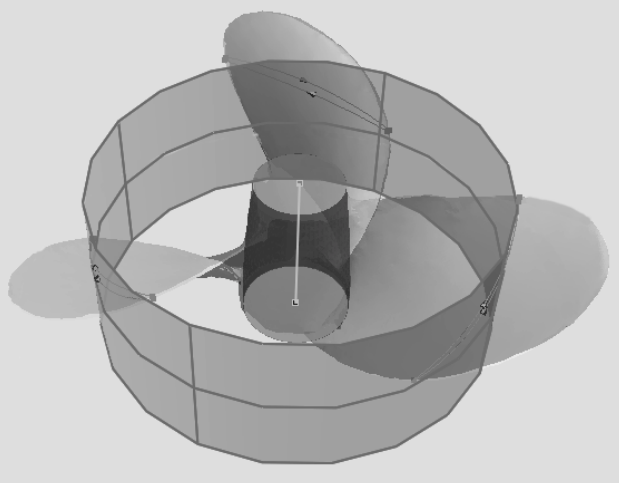


Figure 9: The screw-propeller sliced by a cylinder.

The geometrical analysis of the photogrammetric screw-propeller model was performed in order to measure both pitch and maximum thickness (measured separately on each blade). The measurements were carried out at a distance of 70% of the screw-propeller radius for which thickness and pitch are usually reported on the design geometry by naval architects. This meant to slice the model with a cylinder having a radius 7/10 of the screw-propeller radius (Figure 9), coaxial to its boss.

Measurements on the photogrammetric model were also compared with those obtained by using a CMM proper for screw-propeller models (Figure 10).

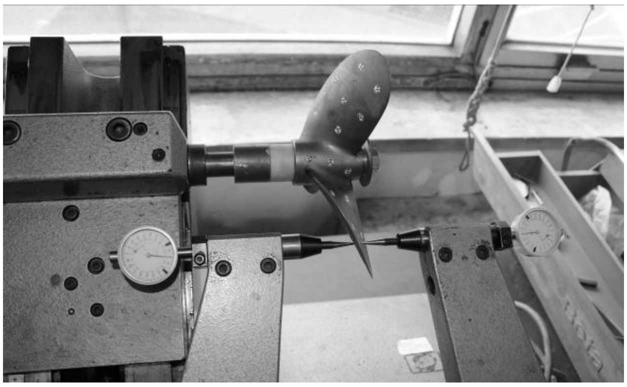


Figure 10: Coordinate Measurement Machine (CMM) specific for screw-propeller models.

In Table 1 the values obtained by the two different methodologies and the differences in mm are reported.

	Blade 1	Blade 2	Blade 3
Pitch by CMM	182.37	181.19	182.49
Pitch by photogrammetry	182.64	180.91	182.13
Pitch differences	**0.27**	**−0.28**	**−0.36**
Thickness by CMM	4.06	3.87	3.95
Thickness by photogrammetry	4.03	3.88	4.06
Thickness differences	**−0.03**	**0.01**	**0.11**

Table 1: Blades pitch and thickness in mm (measured at 70% of radius from the screw-propeller axis).

4 CONCLUSIONS

The experimentation has shown the capability of photogrammetric approach to provide for high resolution 3D models. The accuracy and the reliability have been validated for the screw-propeller model where the differences with respect to the measurements, carried out with a coordinate measurement machine, were below the ITTC tolerances.

ITTC tolerances for towing tank models manufacturing require very high accurate survey (up to 0.1 mm) for inspecting and analysing operations: photogrammetry confirms the capability to supply for such accurate surveys but it can be also used for full scale ships preserving the required shipbuilding tolerances.

5 ACKNOWLEDGMENTS

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