LOW COST REVERSE ENGINEERING TECHNIQUES FOR 3D MODELLING OF PROPELLERS

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ABSTRACT:

In aeronautics and shipbuilding fields quality control of propellers is an obligatory step, a hard task up to some years ago: the shape of each blade has to be measured with high accuracy and referred to a global frame. Specific CMMs were used in the past to perform such complex analyses. When propellers were mounted on ships on dry dock, inspections became nearly impossible to be performed. In this work, both photogrammetric and laser scanning low cost methodologies for 3D reverse modelling of complex objects with high level of detail are proposed. Three photogrammetric software for both commercial and research uses, have been tested in this study for generating high density point clouds. The feasibility of using a low cost triangulation scanner for high accuracy purposes has been studied in the case of small screw propellers. The problem of bringing together all the measurements in a single reference frame with high accuracy is solved by means of colour information. The study shows that a hybrid approach that integrates both photogrammetry and laser scanning methods is necessary. Screws of different sizes, surveyed in laboratory and on the field, such as in dry docks, are modelled and inspected. Different procedures for determining geometrical parameters are shown. Geometrical characteristics derived by 3D models of screws, are compared both with those expected by original plans and CMM measurements.

1. INTRODUCTION

1.1 3D measurements for shipbuilding application.

In the shipbuilding field, as well as in other sectors (aeronautics, mechanics, automobile), there are several circumstances where accurate and reliable three-dimensional (3D) measurements are required.

Ranging from medicine applications (face reconstruction, prostheses, etc.), "terrestrial" and geodetic topics (Digital Terrain Models – DTM, GIS applications, etc.), up to architecture and archaeological fields (surveys of historical buildings, sites, statues, etc.) hundreds of papers and works prove an extensive and tangible interest in the potentialities offered by the "reverse engineering" techniques.

Today, technical-scientific progress permits the realization of efficient, high-performance engineering works. Even the finest detail must be thought out, designed and realized with care. Nevertheless, during the production stage, the manufacturing of materials, assembling, joining and soldering can introduce some differences compared with the original design; quality control must be performed to guarantee that the product complies with the standards.

From simple distance measurement up to the control of micrometric deformation, symmetry, etc., all the operations that allow the measurement and analysis of geometric forms are called reverse engineering of shapes.

Nowadays, different techniques exist for high accuracy reverse engineering purposes. Coordinate Measurement Machines (CMMs) are the most reliable technologies but their use is limited to specialized laboratories and for small objects.

Effective alternatives can be found in new digital technologies for 3D modelling such as active sensors and digital photogrammetry. Active sensors or range-based methodologies are considered the most common techniques for 3D modelling purposes as these instruments give directly 3D data (in the form of a point cloud) combined with colour information and can capture relatively accurate geometric details. Moreover, active

sensors are rather easy to use, although they are expensive and characterized by a limited flexibility.

Up to some years ago digital photogrammetry or image-based 3D modelling, required a massive user's activity and control (manual measurements) during the modelling workflow, reducing its use only to experts. Moreover, photogrammetry has been generally used to measure only few points previously targeted on the object. In recent years, thanks to the advent of the digital era, photogrammetry has been undergoing a rebirth. Today new algorithms for digital image analysis allow fast and accurate semi-automatic or automatic measurements and also 3D data in the form of point cloud are achievable.

Besides this, photogrammetric sensors can be used in different environments (space, air, underwater), installed on diverse platforms and furthermore they can image objects of any size and at different distances simply using different lenses. For these reasons, image-based technique can be very useful in cases of (i) large size objects (full scale ships, monuments or architectures, etc.); (ii) low budgets; (iii) environmental and location conditions disadvantageous both for classical and laser survey techniques (restricted spaces, movements of floating docks, etc.); (iv) time constraints for data acquisition and processing.

Among the current methodologies and sensors, an approach selected as the best for the whole range of 3D modelling applications can not be found at the moment. The choice of a methodology rather than another depends on several factors (object size, required accuracy, kind of analysis to be performed, budget, time execution, etc.), which have to be clearly defined by the customer when the survey is commissioned. In many circumstances, the best approach consists in combining different modelling techniques and sensors to gain the best results in terms of accuracy, time and costs by exploiting the intrinsic capability of each single methodology.

Over the last few years, the shipbuilding field has seen remarkable experimentation in reverse modelling, especially using active sensors, such as laser scanners and pattern projectors (Hand et al. 2005; Guidi et al. 2005). In a few cases,

testing involved photogrammetric technique, and, at any rate, the surveys consisted in marking a small number of point-targets, previously positioned on the object's surface (i.e. circular coded targets), to measure sections or lines of interest (Zaplatić et al. 2005; Mugnier 1997; Lombardini and Unguendoli 1988). These were then processed using appropriate modelling software, implementing several methods, such as interpolation, approximation, or manual design through NURBS surfaces.

For instance, photogrammetric and topographic techniques allow quality control in assembling pre-fabricated ship elements, in order to minimize corrective actions at the shipyard.

Metrology applications require careful planning of the survey operations, since high accuracy is generally required. In such cases, photogrammetry or laser trackers are the most common techniques. In particular, laser trackers make it possible to measure points with an accuracy of 0.1 mm at a distance of 10 m, but they are very expensive. Sometimes, large size objects (assembly parts up to 30x40 m) have to be measured in restricted spaces and/or disadvantageous environmental conditions. It could also be necessary to carry out an in-depth survey of appendages, propellers, the hull or hull parts, in order to verify whether deformations or structural damage have occurred. Such an analysis can be achieved only by means of a high point density survey (dense point cloud) such as laser scanning or image-matching photogrammetric procedures.

In Menna et al. (2009), Ackermann et al. (2008), Fiani et al. (2008) and Menna and Troisi (2007), the authors showed how dense and accurate 3D models of free form surfaces for maritime applications can be obtained using image-matching photogrammetric procedures. In Menna et al. (2009) and Fiani et al. (2008), operational methodologies for integrating laser scanning and photogrammetric techniques were suggested in order to generate 3D models of full-scale hulls. Remarkable benefits can be obtained using this technique, in particular as the time needed to carry out the survey is concerned.

In this contribution, low cost technologies for high precision 3D modelling of fully 3D complex objects are shown in the case of marine screw propellers. The complex geometry of these objects and the high accuracy required on the whole 3D model demand the entire workflow of surveying and 3D processing being carefully planned. Indeed the 3D modelling pipeline is composed of several stages, each of them being source of unavoidable errors that reduce the final accuracy. In particular for 3D complex objects, point clouds have to be collected from different points of view and then unified in a single frame by means of similarity transformations. For free-form surfaces Iterative Closest Point (ICP) standard alignment procedures can lead to not reliable results even tough statistical parameters, furnished by the algorithms, are satisfying (Guidi et al. 2005; Fiani et al. 2008).

First, in this paper different low cost techniques and methods for measuring 3D objects are shown: (i) Close Range Photogrammetry (CRP), (ii) laser scanning with a triangulation scanner and (iii) integration between (i) and (ii). Standard procedures for measuring and modelling a small screw, together with our proposed variant are tested and compared between them. Then principal geometric parameters of the screw are calculated and compared both with those expected from design and measured with a specific CMM for small screws. Finally one of the modelling procedures is chosen to reconstruct the geometry of the screws of the 81-foot Italian Navy motor yacht "Argo".

2. SCREW PROPELLER MODELLING

2.1 Description of the test-screw

In previous works (Menna et al., 2009; Fiani et al., 2008, Menna and Troisi, 2007), the authors have developed a photogrammetric procedure for high density 3D measurements of free form surfaces. In (Ackermann et al., 2008) this procedure was used to perform a high density 3D modelling on a small screw propeller, the B3-50, belonging to the B-Wageningen screw series used for towing tank trials. The great challenge of this experimentation derived from its dimensions. The screw, a bronze three right-handed blades with pitch and diameter of 180 mm had to be measured with a 0.1-millimetre accuracy, as established by the ITTC community. Main geometric characteristics of the screw, known from the manufacturer specifications and then measured with a specific CMM for small screws, were compared with those obtained from the above-mentioned photogrammetric procedure. The study showed that CRP is able to retrieve high accurate measurements complying with standards required by the sector. Since this screw has many interesting characteristics (metallic reflecting surface, poor texture, complex geometry, etc), challenging both for photogrammetry and laser scanning, it has been chosen as test-screw for studying and comparing different survey techniques and methodologies.

In the next paragraph, the photogrammetric procedure will be briefly recalled. The 3D model obtained with this method will be used all through the paper as reference for successive comparisons. A feasibility study on which technique and/or method can be used for reverse engineering of screws will be based on the measurements obtained with the reference method.

2.2 An integrated high density 3D modelling photogrammetric procedure.

In Ackermann et al. (2008) the authors applied their own developed photogrammetric procedure to the test-screw.

The accuracy of 0.1 mm required for this survey demanded a very large image scale. Therefore a Fujifilm S5600 5 MPx digital camera with a 1/2.5" CCD sensor was chosen for the survey. With objects of reduced dimensions and large image scales, small sensors have to be preferred to the bigger ones due to the larger depth of field (DOF). Indeed, at the same conditions (field of view, and aperture value), the DOF is greater for small sensors. A blurred image caused by a limited DOF can be useless for image matching procedures. Therefore as far as quasi-macro/macro photogrammetry is concerned, an amateur camera can be even better than a much more expensive larger sensor semi-metric camera.
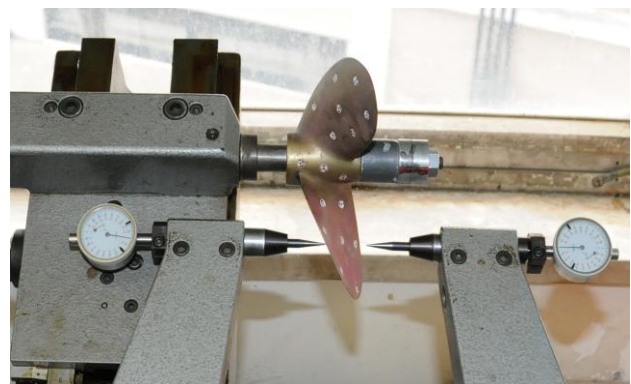

Figure 1: Specific CMM used for reference measurements on the test-screw propeller

Firstly, the camera was calibrated by means of a bundle adjustment with self calibration using a 3D small test-field then 57 circular coded targets were positioned on the screw and two sets of images for a total of 63 photographs were taken with zoom set wide open at 6.3 mm of focal length.

A reference frame (Z axis coincident with the rotation axis of the screw propeller) for the object coordinates was determined by measuring some geometrical features such as points and curves on the screw. The next stage was to perform image matching on the image sets of the blades by using the SOCET SET commercial package specific for aerial photogrammetry. In aerial photogrammetry, Z axis is always up, toward the cameras; therefore, for each suction and pressure face of the blades different reference systems were defined (figure 2, left). This means that a similarity transformation (rotation and translation) was applied to the EO parameters.

A set of 30 images (named the global set) was specifically taken to guarantee the best network of camera stations and consequently the best intersection among optical rays; the other sets (named blade sets) of 33 images was taken to perform image matching on each blades of the screw. All sets of the images of the screw were oriented using the commercial package Photomodeler 5.2.3. Scaling information were obtained from a 100 mm calibrated scale bar imaged together with the global set of images. The maximum spatial residual on the 3D coordinates of circular coded targets was 0.02 mm.

For each face of the blade, in its own reference frame, a point cloud was measured automatically using image-matching procedure in SOCET SET NGATE (figure 2, centre). All the point clouds were then carried back to the original reference frame applying the inverse transformations (figure 2, right). The final point cloud was filtered, edited and triangulated, finally some fundamental geometrical features such as diameter, inclination of the generator line, average pitch, thickness were measured on the 3D model.

A comparison between such measurements and those performed with a CMM showed that the photogrammetric procedure satisfied the required accuracy. The analysis pointed out that one blade was wrong assembled. An important analysis procedure consisted in sectioning the screw by a cylinder whose radius is the 70% of the screw radius (figure 3, left). The curves obtained by such an intersection were then mapped onto the plane in MATLAB environment giving a two-dimensional representation useful for comparing measurements on the virtual model with CMM ones (figure 3, right).

Table 1 summarizes principal comparisons performed on the screw. The inclination of the generatrix was also measured and agreed with the design one (15 degrees).

	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)
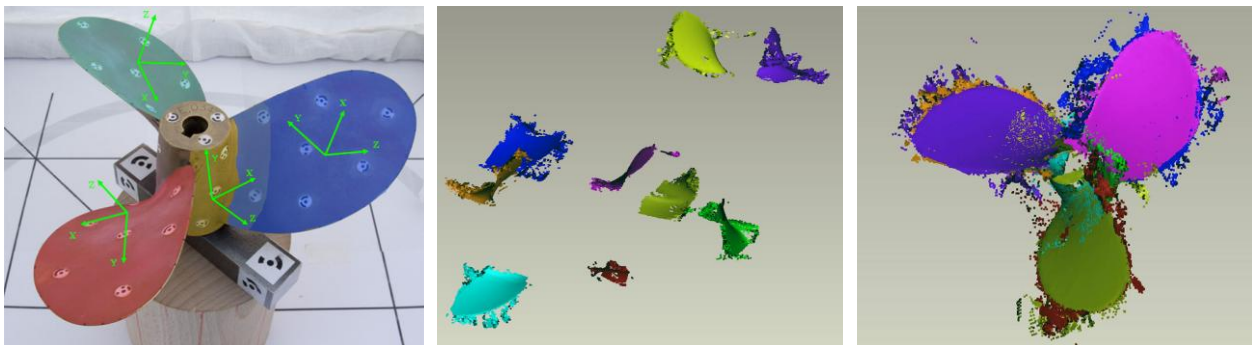

Figure 2: Reference systems used for image matching generation on the screw (left); point clouds generated in different reference systems (centre); point clouds in a unique reference system after the analytical registration
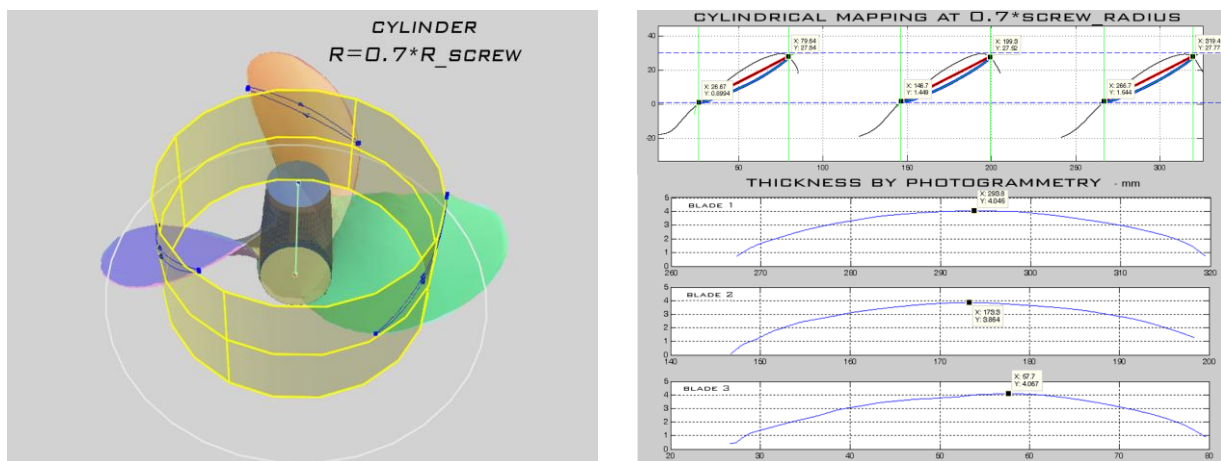

Figure 3: Cutting cylinder at 0.7R (left); cylindrical mapping of section curves (right)

3. LOW COST MODELLING OF SCREW PROPELLER

3.1 Low cost photogrammetry: PhotoModeler Scanner

Photomodeler from EOS systems Inc. is a commercial package for close range photogrammetry applications. The software provides image based modelling and in its new version, named Photomodeler Scanner, features a new tool for measuring 3D point clouds from image pairs. Images for DSM generation should be taken in stereo configuration, meaning that large angles between optical axes should be avoided. No multiple-image matching is allowed. The same images and project of PhotoModeler 5.2.3 used in the reference method were imported into PhotoModeler Scanner.

The software suggests to run its own "Idealizing" tool for removing radial and decentring distortions from images before performing DSM generation. All the possible image pairs per blade (a total of 50) were used for the image matching. Sampling rate was set to 0.25 mm producing a total of 1,4 million point. Point clouds were then processed as in the reference method to generate the final mesh.

The advantage of using PhotoModeler Scanner is that all the point clouds are in a unique reference frame. Either alignment or similarity transformation are not required.

3.2 Low cost photogrammetry: ARC 3D WebService

ARC 3D (homes.esat.kuleuven.be/~visit3d/webservice/v2/) [Vergauwen and Van Gool, 2006] is a group of free tools which allow users to upload digital images to a server where a 3D reconstruction is performed and the output reported back to the user in few hours. ARC 3D also provides a tool for producing and visualising the 3D scene using the data computed on the servers. ARC 3D computes the reconstruction over a distributed network of PCs and depending on size, number and quality of the images that have been uploaded, a typical job may take from 15 minutes to 2 or 3 hours. If the reconstruction has been successful, the system notifies the user by email and the data can be downloaded and used with the model viewer tool. The system is fully automated, therefore its success is strongly related to the input images. At least four images have to be uploaded and a minimum of 5-6 images is suggested. The angle between optical axes should be quite small and the scene should not be planar otherwise the system will not work. The focal length should be constant and no rotations between the images should be present.

MeshLab (http://meshlab.sourceforge.net/), an open source tool developed by the CNR-ISTI in Pisa (Italy) for the processing and editing of unstructured 3D triangular meshes, is also recommended for the visualization of the 3D results of ARC 3D. In our test each blade set of 4 images was uploaded to the server. After the reconstruction the server sent back a zip archive for each set of images containing the range maps, camera interior and exterior orientation parameters. The v3d output format was opened in MeshLab to obtain a mesh exportable in ply format with colour information. Default parameters were used for building meshes.

Since no metric information can be given before the reconstruction, each generated mesh is in an arbitrary reference frame and scale. The only way for scaling each mesh is to know the distance between at least two points on it. To reconstruct the whole screw all the meshes must be aligned in an unique reference system. In this experiment the method proposed for scaling and aligning each mesh consists of using external information on the 3D coordinates of some Reference Points

(RPs) visible on the meshes. The 3D coordinates of the circular coded targets obtained from the bundle adjustment of the reference method described in (2.2), were used as RPs. The procedure used for determining accurately the 3D coordinates of each coded target centre on the meshes is the following (figure 4):

i)   coded target recognition by means of colour information (RGB);

ii)   least square plane fitting (with outlier removal) using the points lying on the target (supposed to be flat);

iii)   points projection on the plane;

iv)   centroid determination using colour information of the circular coded target (black and white).

A specific software, based on procrustean method, was implemented in Matlab to compute the spatial transformation (Rotation, Translation and Scaling factor) for each face of the blades. At least seven point pairs per mesh were used for the computation. Finally the standard deviation of residuals was below 0.1 mm for all the blades. After this procedure all the blades were in the same frame determined in the reference method (2.2).
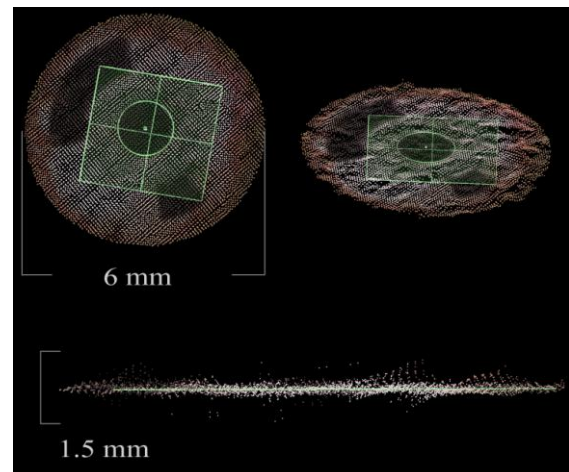

Figure 4: Determination of 3D coordinates of target centre

3.3 Low cost laser scanning: NextEngine Desktop 3D laser scanner.

The Desktop 3D Scanner used in this experiment is based on the NextEngine® proprietary Multistripe Laser Triangulation (MLT) technology. The instrument (figure 5) is a low cost scanner, presented as a "desktop scanner" able to digitize small objects in two categories: "shoebox" and "soda can" size. It is very portable, being small and of light weight, and has a turning table which is wired to the scanner and is controlled by the proprietary software included. The instruments is equipped with a twin array of 4 solid state lasers (class 1M, 10mW) with λ=650 nm and two 3 Mpixel CMOS RGB image sensors. The system acquires in two different modes corresponding to two different baselines: wide and macro mode respectively. For each mode, some constraints on the distance between the object and the scanner are given. The ideal positions for wide and macro mode are respectively 45 cm and 16 cm far from the object. Guidi et al. (2007) investigated the performances of this scanner for cultural heritage documentation. As the investigation required an accuracy of 0.1 mm, the "Macro Mode" was chosen to digitize the screw (dimensional accuracy declared by

manufacturer is 0.127 mm in "Macro Mode"). 11 scans were taken on the screw at the best allowed spatial resolution and aligned with a standard ICP procedure implemented in the proprietary software ScanStudio HD provided with the scanner. The global precision value furnished by the software after the alignment was 0.18 mm. Alignment was also performed in other commercial software giving not significantly different results. The final 3D model counted more than 4,5 million points.

Successively, the 3D model was imported in a reverse engineering software in order to determine the design reference system (determination of Z axis). Firstly, two least square planes with outliers removal were fitted to the points at the top and the base of the boss, then circular planar curves were fitted to the hole of the shaft seat. In this way the Z axis coincided with the reference axis on the design. After this operation a Z rotation was still necessary to bring the 3D model into the design frame. An average rotation was estimated on 9 circular coded targets well distributed on the three blades.
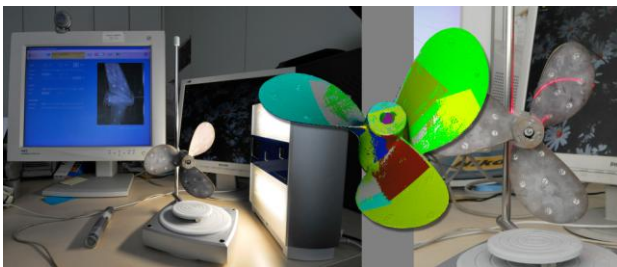

Figure 5: Low cost laser scanner and 3D model of the screw

4. PERFORMANCE ANALISYS AND COMPARISONS

Each single 3D model, obtained respectively with PhotoModeler, ARC 3D WebService and Next Engine Desktop 3D laser scanner, were compared with the 3D model obtained with the reference method described in (2.2).

Since all the 3D models are in the same reference system, a mesh to mesh comparison based on the shortest distance was performed among each single face of the blades. Low cost photogrammetric methods (PhotoModeler Scanner and ARC 3D WebService) agree with the reference one as visible in figure 6. A difference greater than the tolerance was encountered on the back suction faces for the 3D model obtained with the NextEngine scanner. From a first comparison on the three faces of the blades (figure 7, left) the differences were centred at zero and the standard deviation were those expected from manufacturer specifications. Instead, on the back-suction faces differences become greater and a systematic error is evident (figure 7, right). This effect impacts on the measurement of thickness as visible from the analysis at 70% of the screw radius (figure 8). A maximum difference of 0.36 mm was encountered on the first blade and 0.17 millimetres on average for the other two blades. Probably, these differences were generated by the ICP alignment procedure itself as already showed in (Guidi et al., 2005). By using the alignment procedure described in (3.2) and taking advantage of colour information provided by the NextEngine Desktop 3D laser scanner, the differences fall within the tolerance.
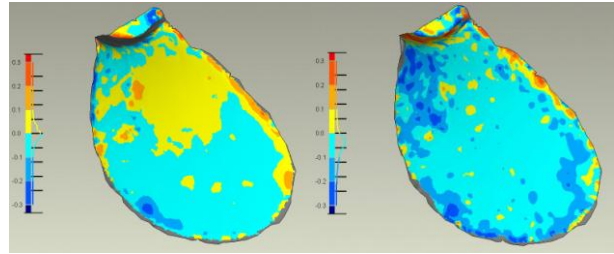

Figure 6: Comparison (mm) between the photogrammetric reference method and PhotoModeler Scanner (left) and ARC3D WebService (right) on a blade of the screw
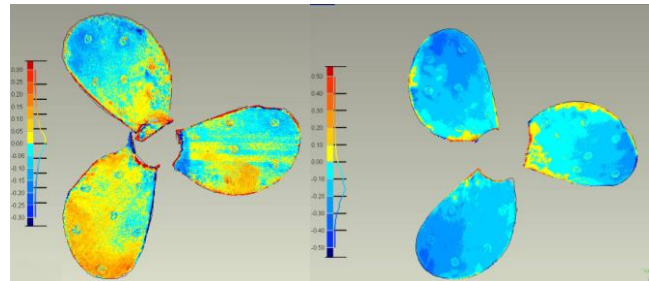

Figure 7: Comparison (mm) between the photogrammetric reference method and laser scanning mesh on the pressure faces (left) and back suction faces (right)
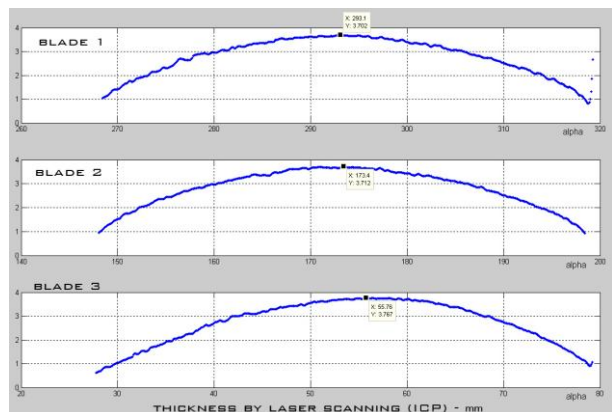

Figure 8: Thickness on the blades from laser scanning mesh

5. 3D MODELLING OF SCREW PROPELLER IN THE DRY DOCK: THE NAVE ARGO CASE

In march 2008, the "Nave Argo", the Official Italian Presidential Unit, was docked in the Navy Yard of La Spezia for a week, during which measurements of her hull and screws were carried out together with the other ordinary maintenance operations. The survey of the "Nave Argo" was carried out to study any hull deformations which may have occurred during her lifetime. Also, some modifications to her hull and propellers have been carried out over time, not shown in the present designs. In particular, the crew noticed overheating of the engine, supposedly caused by screw propellers, probably not suited to the current form and displacement of the "Nave Argo". The main difficulty in surveying screws mounted on a ship arises from restricted spaces and occlusions generated by the blades and the screw propeller axes holders (figure 9).
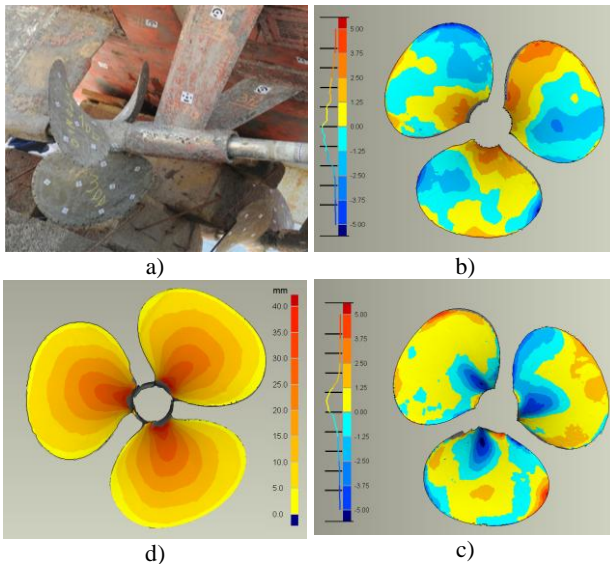
Figure 9: Photogrammetric 3D modelling of the screws of nave Argo (a); comparison (mm) between righthanded and lefthanded screws (b-c); thickness analysis of right screw (d)

These difficulties together with the movement of the dock suggested to use photogrammetry as surveying method. The survey was carried out with a Nikon D300 and a 35 mm lens. About 60 images per screw propeller were taken with both parallel and convergent axes. Since the accuracy required was one millimetre, an average image scale of 1/30 was chosen giving a Ground Sample Distance of 0.2 mm. The worst spatial residual after bundle adjustment (PhotoModeler) was 0.065 mm that means a relative precision of 1:12000. The photogrammetric reference method was used to obtain DSMs of the blades and build the 3D models. The inspection of these 3D models allowed to draw the actual design (lines drawing, thickness and main geometrical characteristics) and compare the two screws between them. Indeed the right screw is righthanded and not directly comparable with the left one that is lefthanded. The only way to do the comparison, after putting them in a same frame, consists in mirroring one of the two screws respect to a plane orthogonal to its axis (figure 9, b-c).

6. CONCLUSIONS

In this work a feasibility study on low cost techniques for high accuracy 3D measurements has been carried out. The case of small screws has been used as test to point out all the limits as well as potentialities of the actual low cost technologies.
Four different methods have been used for modelling a small screw propeller: three photogrammetric procedures based on different software and one based on a low cost triangulation laser scanner.
The procedures are all able to generate high accuracy digital surface models (DSM): on the other hand the creation of a complete 3D model, in the case of such complex objects, requires the composition of more than a single DSM. This study highlight that the standard procedure for DSM alignment (ICP) does not always furnish reliable results. The need of integrating colour information in the case of free-form surfaces becomes evident. The low cost photogrammetric methods, shown in this paper, all satisfy the accuracy and reliability required. In the case of ARC 3D WebService an accurate and reliable coordinate measurement technique is necessary to bring all the DSMs in a single reference system. The PhotoModeler Scanner

method has several limits due to the single pair image matching but takes advantage of generating DSMs in a single reference frame.
If geometrical characteristics such as pitch, generatrix, etc. have to be measured, then methods that collect only point clouds like laser scanning or ARC 3D WebService have to be integrated with other methods such manual or semiautomatic photogrammetric plotting of border curves of the blades.

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