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Reconstruction of 3D Models of Fishing Boat Propellers Using Photogrammetry and Reverse Engineering Techniques

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The conventional method for measuring propeller geometric parameters involves utilizing specialized equipment or 3D measuring devices. Currently, specific propeller geometry parameters can be assessed by employing virtual measurements performed on a virtual propeller model generated using reverse engineering methods. This paper introduces a novel approach to constructing 3D models of small fishing boat propellers using photogrammetry and reverse engineering techniques. In this method, the propeller is captured through photographs taken with a smartphone camera employing special techniques. Subsequently, these images are processed using Agisoft Metashape to generate a mesh model, from which a precise photogrammetric model of the propeller is developed using CATIA. By comparing the photogrammetric model with the scanned model in GOM Inspect, and evaluating the measurement outcomes of blade radius and pitch on virtual and physical models, it is possible to ascertain that the photogrammetric model exhibits exceptional accuracy. Consequently, the photogrammetric model can be effectively utilized for the measurement of propeller geometric parameters.

Keywords: Photogrammetry, Reverse Engineering, Smartphone, Fishing boat, Propeller

1 Introduction

A marine propeller consists of helical blades and a rotating hub on a propeller shaft. Its purpose is to propel a ship by utilizing the power generated and transmitted by the ship's main engine. In shipbuilding and repair, it is crucial to inspect certain geometric parameters of a propeller, including diameter, pitch, rake, blade area, and blade thickness, to ensure that it meets the requirements of the propulsion system. Coordinate measuring machines (CMMs) are commonly used to measure these parameters [1, 2, 3], although they can be expensive and have limited measuring ranges. Alternatively, non-contact methods such as 3D scanners [4, 5, 6], machine vision systems [7, 8], or digital cameras can also be employed for propeller inspection. Three-dimensional (3D) scanning and machine vision systems can create high-accuracy models of propellers, but they are costly. Photogrammetry is a technique that involves creating a 3D model of an object by using a series of photographs captured by a digital camera. It enables the creation of detailed and realistic 3D models that can be used for visualization, analysis, and documentation purposes [9-11]. Using photogrammetry techniques can reconstruct marine propellers which are less accurate but it is a very cheap way of measuring marine propellers [12].

Reverse engineering serves as a valuable tool across various engineering disciplines, enabling the conversion of physical components into digital representations through the creation of virtual models. These models can be used for further computer-aided applications [13-15]. A novel method using photogrammetry and computer aided design (CAD) for measuring the pitch of a fishing boat propeller was proposed in our previous study [16]. In this method, by using Agisoft Metashape (Agisoft LLC, Russia), the 3D model of a propeller can be reconstructed from a series of photos taken with a smartphone camera. However, this is an incomplete model because only the thrust side of the propeller is formed. The capturing techniques in the proposed method do not allow combining images of both sides of a propeller into a unified model in the image processing environment. This limitation needs to be overcome to build a complete propeller model to measure some other geometric parameters of the propeller besides the pitch. This research aims to present an innovative solution for the accurate reconstruction of fishing boat propellers with fixed pitch design in comprehensive 3D models. By employing the powerful capabilities of photogrammetry and reverse engineering techniques, along with the utilization of Agisoft Metashape and CATIA (Dassault System, France) software, a robust method is developed. The reconstructed model can be used in a CAD environment for measuring some geometric parameters of a propeller such as diameter, pitch, rake, blade thickness, and area of blade.

2 Methodologies

It was necessary to process the image (create a model) based on the pattern and then incorporate the accuracy requirements.

2.1 Image capturing techniques and processing

For image capturing, propellers were captured indoors using a smartphone camera, a cylinder, and 3 light-emitting diodes (LEDs) with an arrangement shown in Fig. 1.

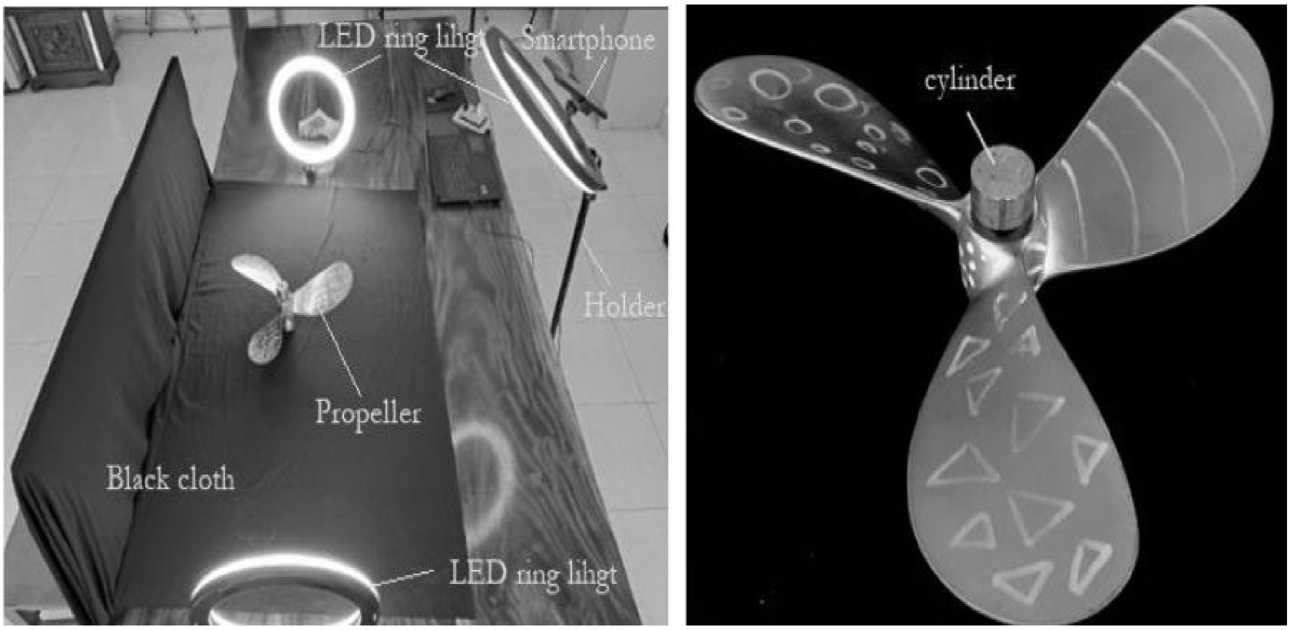


Fig. 1 *Image capturing arrangement*

The propeller being studied was positioned on a table, with a black cloth placed underneath and behind it to eliminate any unwanted foreground elements and reduce background noise. Three 18 W LED ring lights were strategically placed on three sides of the propeller, each at a distance of approximately 0.7 m. Two of the lights were placed on the table, while the third was clamped onto a stand holder. The smartphone used for capturing images was securely mounted on the phone holder that came with the LED ring light setup.

In order to reconstruct an object using digital photogrammetry, it is necessary to capture photographs of the object from all angles, covering a complete 360-degree rotation. Based on our past observations, it has been evident that when utilizing a smartphone camera to capture pictures of an immobile object, there may exist inconsistencies in the lighting across the distinct elements of the image. The fluctuations in lighting could potentially hinder processes like object reconstruction or the development of incomplete models. Inconsistencies in lighting negatively impact the accuracy of reconstructing models [17, 18]. To address this issue, a specific approach has been implemented in this study. After each photo, the propeller was manually rotated at an angle from 5° to 10°, ensuring that the smartphone camera remained stationary and the scene remained unchanged. This method helps to minimize any discrepancies in lighting and ensures more accurate image processing results.

Small fishing boats commonly use propellers made of cast bronze, which ordinarily have smooth surfaces and have nearly no textures. To aid in aligning images of the propeller's two sides, various geometric shapes such as arcs, circles, triangles, and dots were sketched onto the propeller blades and hub, as illustrated in Fig. 1. This approach fulfills a requirement suggested by Agisoft to prevent non-textured objects from causing issues during the alignment process [19]. To attain superior accuracy, a steel cylinder was positioned concentrically on the hub, serving as a reference for scaling the propeller model to its actual dimensions. The cylinder possesses a diameter of 25.221 mm and a cylindricity of 0.021 mm, which was determined using a Hexagon Global S CMM.

An Oppo A54 smartphone camera (48-megapixel) was used in this study. Some basic parameters of the smartphone camera were set up as follows: 52 mm focal length, 200 ISO number, 5000 K white balance, automatic aperture, focus, and shutter speed.

Each side of the propeller received three shots in total, each with particular specifications. The first shot involved capturing images from above, with the phone tilted at a 45° angle from the horizontal and positioned at a height of approximately 0.6 m above the table. Moving on to the second shot, the phone was lowered to a height of around 0.4 m above the table, with the tilt angle adjusted to about 60° from the horizontal. Lastly, the third shot was taken with the phone placed perpendicular to the plane where the propeller was located. Throughout the process, the propeller was manually rotated for each shot, while maintaining a consistent distance of 0.7÷0.8 m between the phone and the propeller. After capturing images of the top side, the propeller was then flipped to expose its bottom side, and the same procedure was followed to photograph it.

After capturing photographs, the propeller was scanned using a portable 3D G-Scan scanner (Hexagon AB, Sweden). This step was conducted to generate a scanned model used as a reference model for virtually verifying the accuracy of the photogrammetric model.

This study utilized the image processing method presented in our previous study [16]. Firstly, the photographs of the propeller were imported into Agisoft Mateshape 1.8, and afterward processed to construct the Standard Tessellation Language (STL) model of the propeller. Following this, the STL model was then imported into CATIA V5R2019 to generate an accurate photogrammetric model. The first step in CATIA involved using the Basic Surface Recognition tool to generate the cylindrical surface of the cylinder. Subsequently, the diameter of this virtual cylinder was measured. Lastly, by taking into consideration the diameters of both the virtual and physical cylinders, a scaling operation was executed. This process was executed on a workstation (3.6 GHz CPU, 32 GB RAM, 24 GB GPU).

2.2 Accuracy estimation

In this study, the accuracy of the photogrammetric model was assessed by employing GOM Inspect 2022 (Zeiss Group, Germany). This assessment involved conducting a dimensional comparison between the photogrammetric model and the reference model. GOM Inspect possesses the capability to visually illustrate the disparities between two CAD models by utilizing a colour map [20-22], and to calculate the extreme and arithmetic mean deviations [23]. Additionally, the radii of the propeller and the pitches at 0.7R (R is the propeller radius) of the photogrammetric models were measured in CATIA and compared with the measurements obtained from physical propellers. This comparison was facilitated by employing the Hexagon Global S CMM.

The pitch measurement was performed according to the principle recommended by the ISO 4842 standard, as depicted in Fig. 2 [3]. The primary method of measurement involves tracing a specific length PQ along a helical path with a radius r, representing angle α, and determining the height varian h between points P and Q about a given plane. For per blade and radius, the pitch is calculated by multiplying h by $360/\alpha$. In this case, a 20° angle was selected.

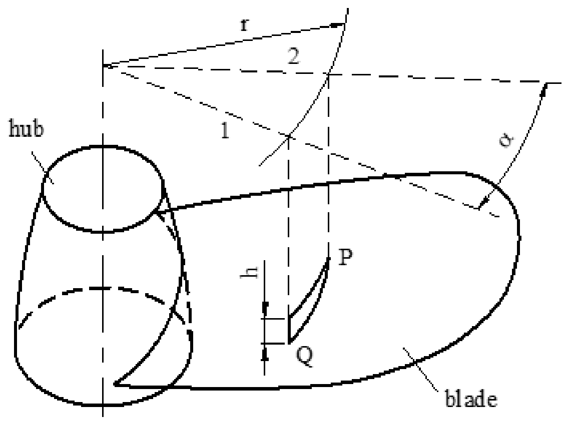


Fig. 2 *Pitch measurement principle [10]*

The measurements of the radii and the pitches on the virtual propellers in CATIA were mostly performed using sketch, constraint, and measurement tools as described in [16]. Fig. 3 illustrates the measurement of the vertical separation between points P and Q for pitch measurement in CATIA.

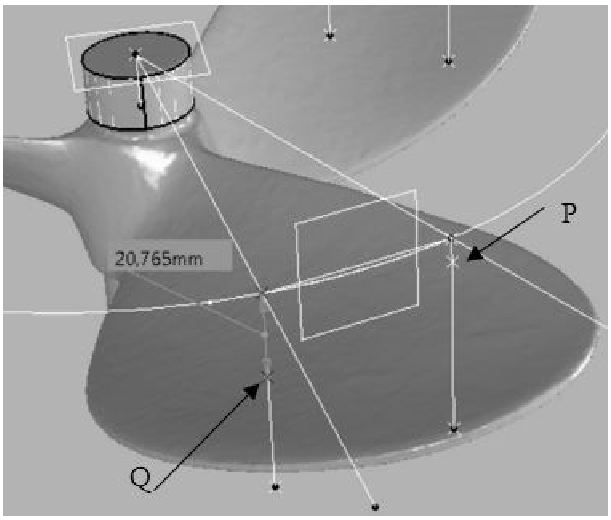


Fig. 3 *Pitch measurement in CATIA*

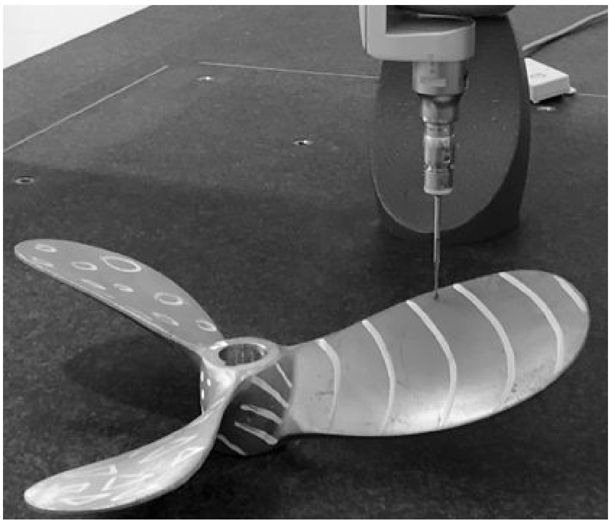


Fig. 4 *Pitch measurement on CMM*

3 Applications

The research utilized several fishing boat propellers as the focal point to demonstrate the efficacy of the suggested approach. An illustrative example is showcased in this paper, featuring a 3-blade cast bronze propeller, about 375 mm in diameter. A total of 241 photographs of the propeller were captured. Among these images, six were selected to be included in Fig. 5, showcasing the propeller in six typical photographed positions.

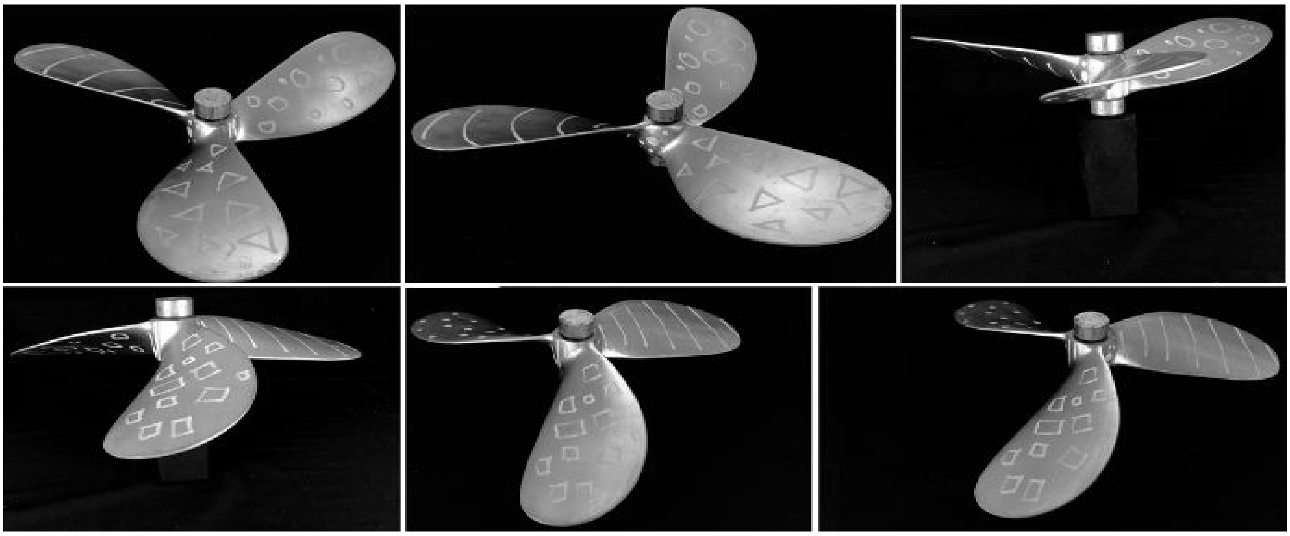
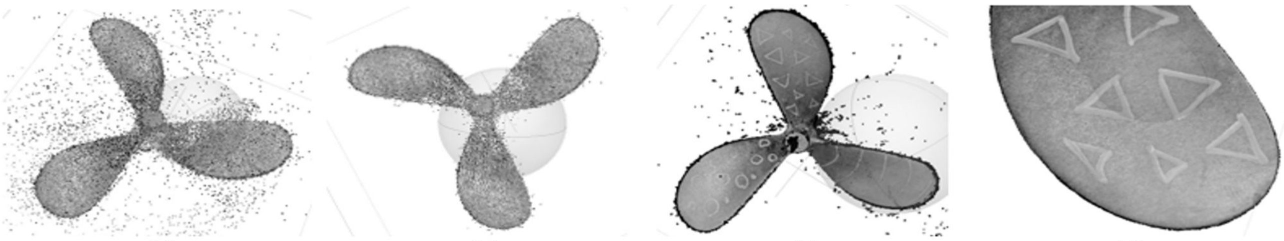


Fig. 5 *Six typical photographed positions*

Agisoft Metashape involves a three-step image processing procedure [19]: aligning images and generating a sparse point cloud, creating a dense point cloud, constructing a mesh, and generating texture. In this study, these steps were executed automatically, but manual intervention was required for noise removal after the first and second steps to minimize noise in the point cloud. This noise typically consists of points that significantly deviate from the surfaces of the propellers. Fig. 6 illustrates the sparse point cloud both before (a) and following (b) noise reduction, as well as the dense point cloud before noise reduction (c) and a specific region of a blade within the dense point cloud after noise reduction (d). The automatic steps were completed in approximately 16 minutes, while the noise removal process following the first and second steps required around 20 minutes and 2 hours, respectively. Following the second step, particular attention was given to reducing noise around the edges of the blades. It is noted that highly skilled personnel can complete the noise removal task in a shorter amount of time.

Fig. 7 shows the texture model and the photogrammetric model, while Fig. 8 illustrates the reference model.



(a) (b) (c) (d)

Fig. 6 *The point clouds and noise reduction*

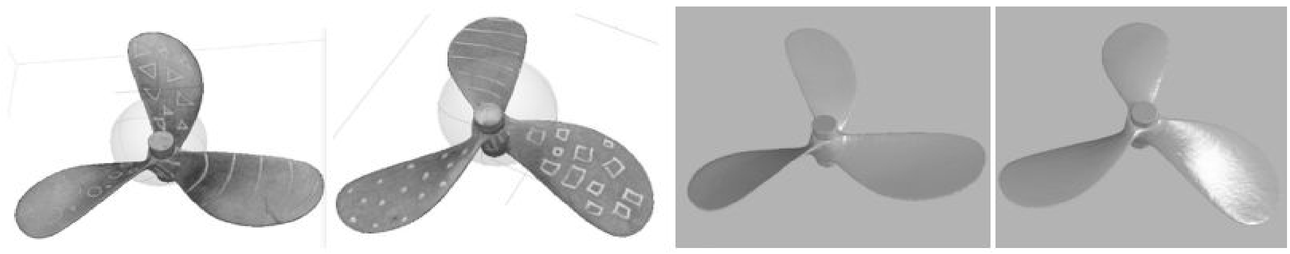


Fig. 7 *Two sides of the textured model (left) and the photogrammetric model (right)*

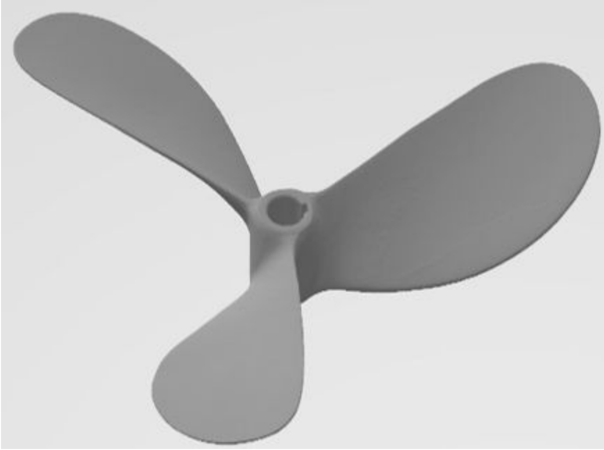
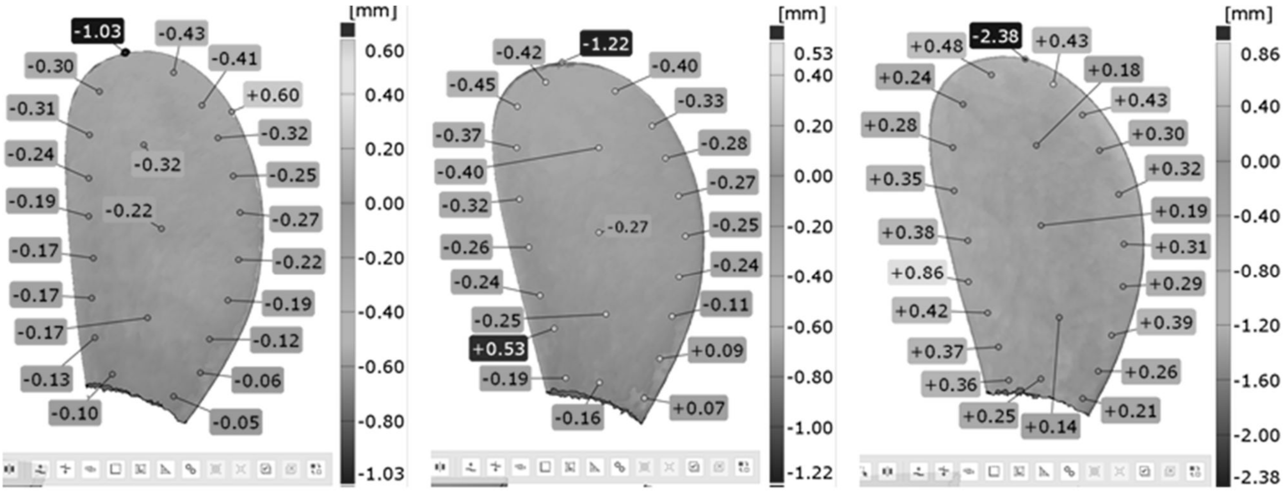


***Fig. 8** The reference model*

GOM Inspect allows for a comprehensive comparison between the photogrammetric model and the reference model. Several experiments conducted during this study have revealed significant errors occurring at the hub section of the propeller. The hub's overly brilliant areas and the darkened portions where the cylinder meets the bore on the hub are blamed for these inaccuracies. In order to assess the accuracy of the model effectively, the study excludes the hub area of the models within a radius of 0.2R. Fig. 9 illustrates the colour-coded representation of deviations and selected deviations between two sets of CAD data. The colour scheme consists of blue, green, and red, which correspond to negative deviation, no deviation, and positive deviation, respectively. Upon observation, it is evident that the light blue and red regions exhibit minor variations, while the dark blue regions display more significant deviations. However, it is crucial to note that the dark blue regions are relatively small, primarily located at the edges of the blades.



Blade 1 Blade 2 Blade 3

***Fig. 9** Colour-coded map denoting deviations*

The deviations depicted on the colour map indicate the presence of modelling errors within the photogrammetric model. These errors are likely attributed to factors such as image acquisition, noise reduction, and scaling procedures. Table 1 provides detailed information on the extreme and arithmetic mean deviations between the reference model and the photogrammetric model.

***Tab. 1** Deviations on the blades*

Blade	Deviations (mm)		
	maximum	**minimum**	**arithmetic mean**
1	+0.60	-1.03	-0.22
2	+0.53	-1.22	-0.27
3	+0.86	-2.38	+0.19

According to Tab. 1, it is evident that the differences in extreme deviation between the two models on three blades are relatively minor, ranging from -2.38 mm to 0.86 mm. The arithmetic mean deviations are also quite small, varying from -0.27 mm to +0.19 mm. The colour maps, in conjunction with these deviation values, indicate that the blades of the two models exhibit a slight disparity, yet possess a considerable similarity in terms of size.

The radii and pitches at 0.7R were determined through both virtual and physical measurements, and the results are displayed in Table 2. Within this table, the values for R_{CAD}, R_{CMM}, P_{CAD}, and P_{CMM} represent the radii (R) and pitches (P) that were obtained from the photogrammetric models in CATIA and the physical model by CMM, respectively. Moreover, the recorded data also highlights differences (Diff) in the mean values of radii and pitches.

Tab. 2 *The radii and pitches at 0.7R [mm]*

	R_{CAD}	R_{CMM}	P_{CAD}	P_{CMM}
Blade 1	187.077	187.527	278.352	279.072
Blade 2	187.529	187.197	277.146	279.702
Blade 3	186.411	186.068	269.746	270.090
Mean	187.006	186.931	275.081	276.288
Diff	+0.075	-	1.207	-

The measurement results indicate very small disparities in the radii values obtained from the photogrammetric model and the physical propeller, only from -0.343 mm to 0.450 mm, equal to -0.18% to 0.24%. The mean radius discrepancy is merely 0.075 mm, representing a deviation of 0.04%. Besides, the average pitch reveals a difference of 1.207 mm, representing 0.44%, while the pitch measurements derived from the photogrammetric model for individual blade show minor discrepancies when compared to the measurements acquired from the physical propeller, ranging from 0.344 mm to 2.556 mm, corresponding to 0.13% to 0.91%. Fishing boats have the option to be equipped with propellers that possess either medium accuracy or wide tolerances. For propellers with high precision, a variance of 0.5% is considered acceptable for radius measurement, as per the ISO 4842 standard. On the tolerances of the pitch, a margin of error of 3% is considered acceptable for local pitch measurement in propellers characterized by a medium level of accuracy [3]. The findings indicate that the virtual model and measurement technique can be acceptable in terms of accuracy.

Ackermann et al. [7] and Menna and Troisi [8] employed a digital camera along with a steel bar for scaling purposes to capture images of a propeller containing coded targets. When comparing the pitch measurements acquired with photogrammetry and CMM, there were only slight differences, less than 0.1%. This indicates that the photogrammetric model demonstrates a high level of accuracy. However, it is worth noting that their approach may involve complexities and time-consuming steps due to the need for calibration during the photography process and subsequent 3D reconstruction in Geomagic Studio. Using a digital camera and coded targets, Faizin and colleagues [24] developed a highly accurate photogrammetric model of a propeller with a blade radius error of 0%. The pitch errors of the virtual model for the three blades were discovered to be 0.9%, 2.4%, and 3.3% at 0.7R, which were slightly larger than the results obtained in our own study. Additionally, Faizin's investigation may be considered labor-intensive as a result of the multiple modelling activities conducted in SolidWorks and Geomagic Studio software, along with the calibration process.

In our previous investigation [16], the pitch error at 0.7R achieved on the photogrammetric model on 3 blades was 0.792 mm (0.24%), 3.390 mm (1.08%), and 5.220 mm (1.67%), respectively, when compared to the pitch measurements acquired on an electrical discharge machine. It is evident that these inaccuracies are greater than those found in our recent investigation. Moreover, the entire photogrammetric model could not be produced using the previous technique. The photogrammetric model in this study is a complete model, and exhibits satisfactory accuracy, suggesting that the proposed method is suitable for determining certain geometry parameters of fishing boat propellers diameter, pitch, rake, blade thickness, and area of blade. This cost-effective approach may be particularly advantageous in situations where specialized measuring equipment is not accessible. Nevertheless, it is important to acknowledge that the proposed method is still time-consuming for the task of image processing.

4 Conclusion

In this paper, a novel method of modelling propellers which consists of photogrammetry and reverse engineering techniques is proposed. The propeller image acquisition process incorporates several key features. Firstly, a black cloth is utilized to create a black background for the image, which serves to minimize noise during image processing. Secondly, a system of three LED lights is strategically arranged on three sides to ensure sufficient lighting for photography. Thirdly, to produce a consistent light field in every picture, the propeller of a smartphone is rotated while the camera is fixed in place. Furthermore, Agisoft Metashape is able to correctly match the full set of captured photos due to the different geometric shapes drawn on the hub and both sides of the blades. Lastly, an accurate cylinder is employed to determine the correct ratio between the real propeller and the STL model. For the illustrated case, the analysis of the photogrammetric model and the scanned model in GOM

Inspect reveals that the average deviation on the blades is rather small, ranging from -0.22 mm to +0.19 mm, and significant deviations are only presented in a small area on the edges of the blades. Furthermore, the comparison of the propeller radius measurements indicates that the average variance between the photometric model and the actual propeller is merely 0.075 mm, corresponding to a difference of 0.04%. The findings from the assessment of the propeller pitch at 0.7R indicate that there is an average variance of 1,207 mm between the photogrammetric model and the actual propeller, representing a 0.44% discrepancy. The photogrammetric model of this study provides a reasonable level of accuracy, according to all the data, indicating that the suggested method is appropriate for figuring out certain geometric parameters of fishing boat propellers. However, manual noise removal during the image processing phases takes a lot of time. The future work of this study will focus on lowering picture noise, which could result in undesired points around the blade edges during image processing. The goal of this work is to speed up the manual noise removal process.

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