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Volumetric Image Processing for Predicting Propeller Roughness Penalties

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ABSTRACT
Roughness of marine propellers can profoundly affect the efficiency of maritime transportation, compliance with environmental regulations, and overall operational expenses. This study aims to develop a graphical user interface (GUI) program using volumetric image processing (VIP) techniques to predict marine propeller roughness values. A three-dimensional model of a Rubert gauge comparator has been created, which is employed for the assessment of roughness grades. The study covers surface roughness parameters, geometric features, and classification algorithms, all integrated into the GUI program. Roughness parameters, such as amplitude and spacing parameters, are extracted from the Rubert gauge's models. Geometric features, including Omnivariance, Anisotropy, Surface Variation, Eigenentropy, and Verticality, are calculated using CloudCompare software. The K-nearest neighbors (K-NN) classification algorithm is employed by the program to categorize previously unidentified propeller blade roughness based on data extracted from the Rubert comparator's specimen. Subsequently, it calculates the power increase and additional resistance due to the surface roughness of the propeller blade. Additionally, the program estimates the cost of propeller polishing. This multidisciplinary approach enhances the understanding and prediction of marine propeller roughness, aiding in efficient vessel operation and environmental compliance.

Keywords
Volumetric Image Processing, Geometrical Modeling, Propeller Surface Roughness, Comparators.

1 INTRODUCTION

Marine propeller roughness presents a significant challenge in enhancing maritime transportation efficiency, encompassing adverse environmental and economic repercussions. It becomes apparent that augmenting propeller roughness renders the propeller noncompliant with the International Maritime Organization's (IMO) mandates aimed at reducing greenhouse gas emissions (GHS). Simultaneously, from an economic perspective, a conspicuous correlation emerges between an increase in propeller roughness grade and a reduction in power term, entailing increased operational capital expenses (Daidola, 2019). The propeller's roughness grade fluctuates in response to the accumulation of fouling on its blades. There are numerous studies related to the subject, specifically those focused on examining the impact of roughness on propellers and determining its performance.

The increase in resistance was predicted using sand grain roughness, as acknowledged by Townsin et al. (1981), who mentioned that fouling on propellers can have a fuel economy impact similar to that of rough hulls but can be addressed more cost-effectively. An analytical approach for assessing the impact of a rough hull and propeller on ship performance was introduced by Mosaad (1986), who acknowledged that while propeller losses may appear less significant compared to hull losses, the losses per unit area are significantly higher. This approach was supported by comprehensive case studies. Atlar et al. (2003) employed a Rubert propeller roughness comparator, followed by drag increase estimations on blade sections and computer software, to quantify the efficiency reduction resulting from fouling on a merchant ship. In 2003, Anderson et al. acknowledged that propeller cleaning provides a significant return on investment for a relatively low cost, along with additional advantages of reduced cavitation and noise.

The aim of this research is to create a graphical user interface (GUI) program designed to predict the roughness values of marine propeller surfaces using volumetric image processing (VIP) techniques. This is accomplished by designing a three-dimensional six specimen Rubert gauge comparator, which is used in practice to determine the roughness grade and related marine propeller roughness penalties.

Section 2 outlines the research methodology, which encompasses the foundational concepts utilized throughout the study, specifically, surface roughness parameters and geometric features. In additions it explores the classification algorithm employed for data categorization in the study. In Section 3, it illustrates the three-dimensional modeling of the six specimens of the Rubert gauge. This is done after capturing their two-dimensional representations from real gauges. Section 4 presents the extracted and analyzed data for the three-dimensional models of the Rubert gauge. It also includes the output data for both the surface roughness parameters and geometric features for each of the six specimens. In Section 5, the utilization of the extracted data is discussed, particularly in the development of a GUI program to achieve the research objective of predicting previously unknown propeller roughness and determining the resulting power increase. This section also addresses the cost of propeller polishing and illustrates the relationship between the propeller numbers of revolution and power increase. Furthermore, three boat propellers with three blades each were employed, each designed in three-dimensional form, with varying degrees of surface roughness. They were tested using the designed program to derive data for each propeller, including the added resistance coefficient and power increase values. The Figure 1 shows the overall proposed sequence of work to achieve the research goal.

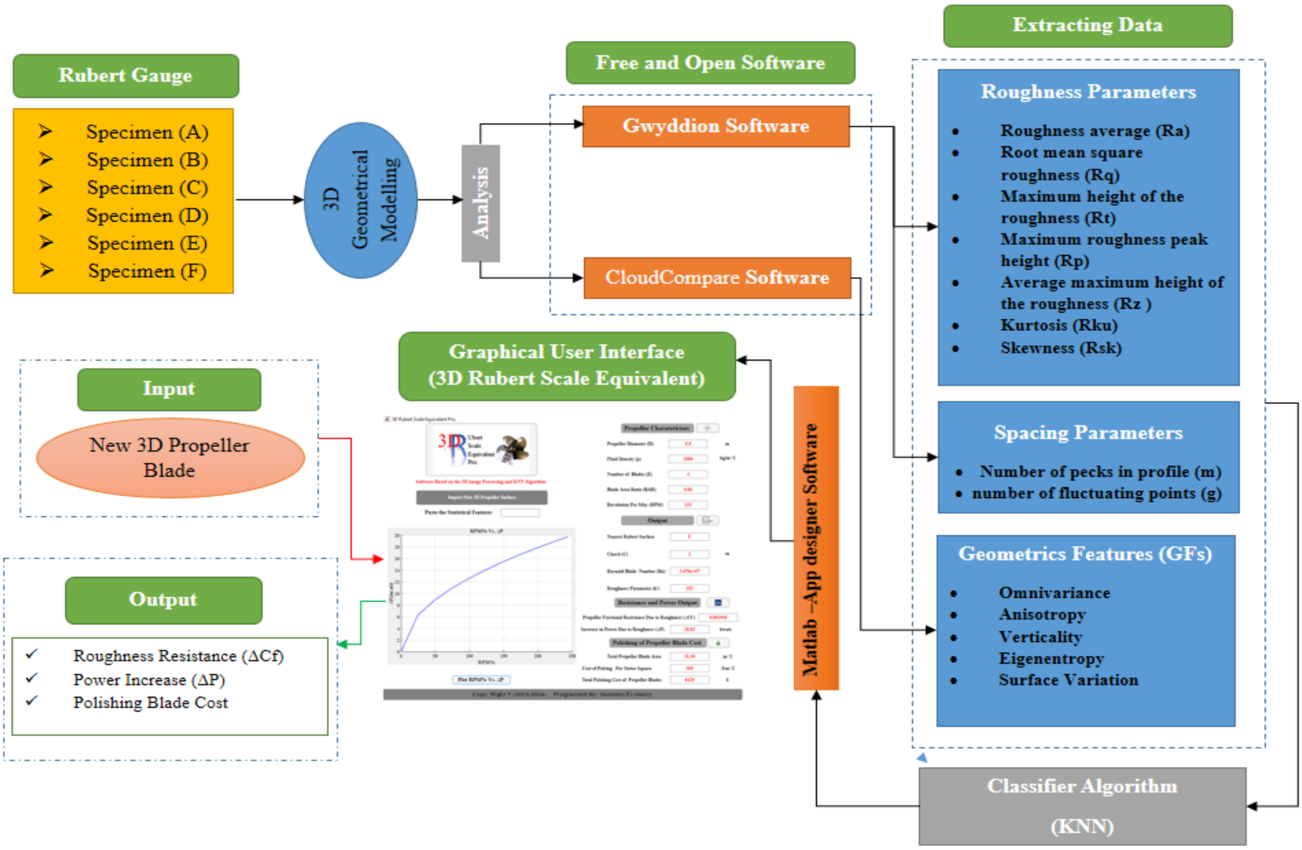

Figure 1: Overview of the proposed sequence of work

2 MULTIDISCIPLINARY APPROACH and METHODOLOGY OVERVIEW

This research covers various multidisciplinary branches that synergistically serve research outputs. These branches include surface roughness characteristic and their applications on marine propellers to determine the resulting drag values. Furthermore, it encompasses three-dimensional modeling, volumetric image processing, and the utilization of classification algorithms. The integration of these operations culminates in the creation of a graphical user interface (GUI). In this context, Section 2.1 presents the data related to surface roughness parameters, followed by Section 2.2 which outlines the method for calculating marine propeller surface roughness. Subsequently, Section 2.3 is dedicated to showcasing the geometric feature parameters, which are employed in Volumetric Image Processing for handling three-dimensional models and discovering the relationships among the 3D points of the cloud. Additionally, Section 2.4 elaborates on the classification algorithm used in the research for data classification.

2.1 Surface Roughness Parameters

The roughness parameters can be estimated in either 2-D or 3-D. The 2-D roughness parameters focus on individual profiles, which are studied through surface roughness parameters. The 3-D parameters are computed by considering the complete surface topology, incorporating multiple parallel 2D profiles. This enables the study of surface roughness through a method called volumetric image processing (VIP), utilizing the concept of geometric features. The surface roughness parameters including amplitude roughness parameters, and spacing roughness parameters (Gadelmawla, 2002). The Amplitude Roughness Parameter is defined as a measurement used to quantify the variations in surface elevation between the highest peaks and the lowest valleys on a given surface. The spacing roughness parameters relevant the horizontal surface deviations and including number of peaks in profile (m) and number of fluctuating points (g). The mathematical implementations of amplitude roughness parameters are shown in Appendix (1), and the spacing roughness parameters are shown in Appendix (2).

2.2 Measurement of Marine Propeller Roughness

Practically, it is a well-established fact that the assessment and the measurement of marine propeller roughness is carried out through a specialized device known as a Rubert roughness comparator as imaged in Figure 2. The Rubert roughness comparator consists of six specimens, labeled A, B, C, D, E, and F, which are numbered from the least roughness A to the highest F. The specimens A and B are related to the surface roughness of new or reconditioned blades of marine propeller while the remaining C, D, E and F are replicas of surface roughness taken from propellers eroded by periods of service. These instruments provide measurements of surface roughness in terms of parameters such as average roughness (Ra), maximum height of the profile (Rz,) and root mean square roughness (Rq). By assessing the degree of similarity analogically between the marine propeller intended for roughness measurement and the specimen, it is possible to calculate the roughness value by applying the following Equation (1) (Mosaad,1986)

$$1000*\Delta C_F=8.1R_e^{0.093}\,[0.33\,(h'/C)-4.5\,R_e^{-1/3}] \qquad (1)$$

Where ΔC_F is the frictional sectional resistance of propeller due to roughness.

R_e is the blade section Reynold number

C is the section chord length

h' is the roughness parameter, and its values are recommended by M. Mosaad (1986) as 1.32 µm, 3.4 µm, 14.8 µm, 49.2 µm, 160 µm, and 252 µm for specimens A, B, C, D, E, and F, respectively.

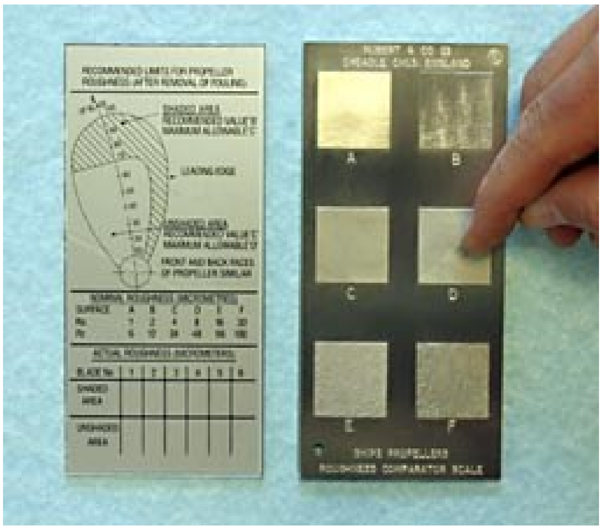

Figure 2: Rubert gauge of propeller roughness comparator

2.3 The Geometric Features (GFs)

The features of 3D geometric models consist of the 3D local neighbor point cloud, which can be represented by the covariance matrix (Jørgensen., 2015). The covariance matrix plays a crucial role in synthesizing the eigenvalues (λ_1, λ_2, λ_3), and these combinations reveal the characteristics and form of the 3D geometry. λ_1, λ_2, and λ_3 represent the unit eigenvalues, eigenvectors, and normal vector, respectively, and they contribute to each other in the classification of 3D geometric models. In volumetric image processing, eigenvalues are utilized to extract features such as Omnivariance, Anisotropy, Surface Variation, Eigenentropy, and Verticality (Dey,2021). Appendix (3) contains the mathematical definitions for geometric features.

2.4 K-Nearest Neighbors (K-NN) Classification Model

The K-Nearest Neighbors (K-NN) model is a widely used machine learning (ML) algorithm in the domain of two and three-dimensional surface classification (Samworth, 2012). Its primary purpose is to classify unknown data points into predefined categories, based on their proximity to the K nearest known data points from the training dataset. The workflow begins by specifying the number of nearest neighbors (K) to be considered during the classification process. Subsequently, the distance between the unidentified data point and each data point within the training dataset is quantified, using distance metrics like Euclidean distance (Liberti et al., 2017).

Afterwards, the K nearest training data points are identified, and a weighted vote is conducted to determine the predominant class among these neighboring points. The class with the highest cumulative votes is assigned as the classification for the unidentified data point.

3 GEOMETRICAL MODELING OF RUBERT GAUGE COMPARATOR

In this research, a realistic Rubert gauge comparator was utilized. As part of the experiment, each specimen was captured within the gauge using a camera and then transformed into a grayscale image with dimensions of 1000x1000 pixels, measuring 25mm in both length and width. The grayscale is used to represent elevations and depressions within a two-dimensional captured image, composed of the two primary colors, black and white, with gradients in between. Grayscale images are captured using the grayscale system for ease and precision in converting them into three-dimensional models. Figure 3 illustrates the captured image of both specimen A and B as an example, and it is done with a gray scale effect.

Grayscale images are utilized and transformed into three-dimensional models in the Rhinoceros software using the "Heightfield" command. Then, they are saved with the Stereolithography (.stl) extension. Figures 4 illustrates the three-dimensional models for all specimen.

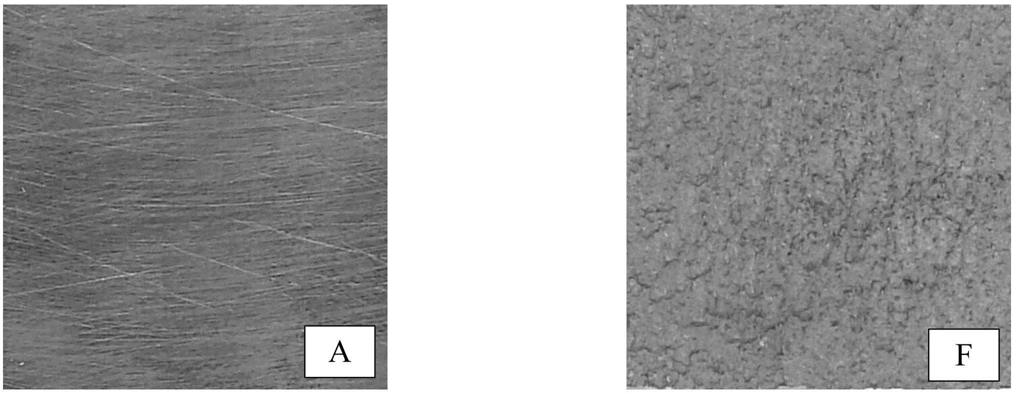

Figure 3: Gray scale of Rubert specimens (A) and (F)

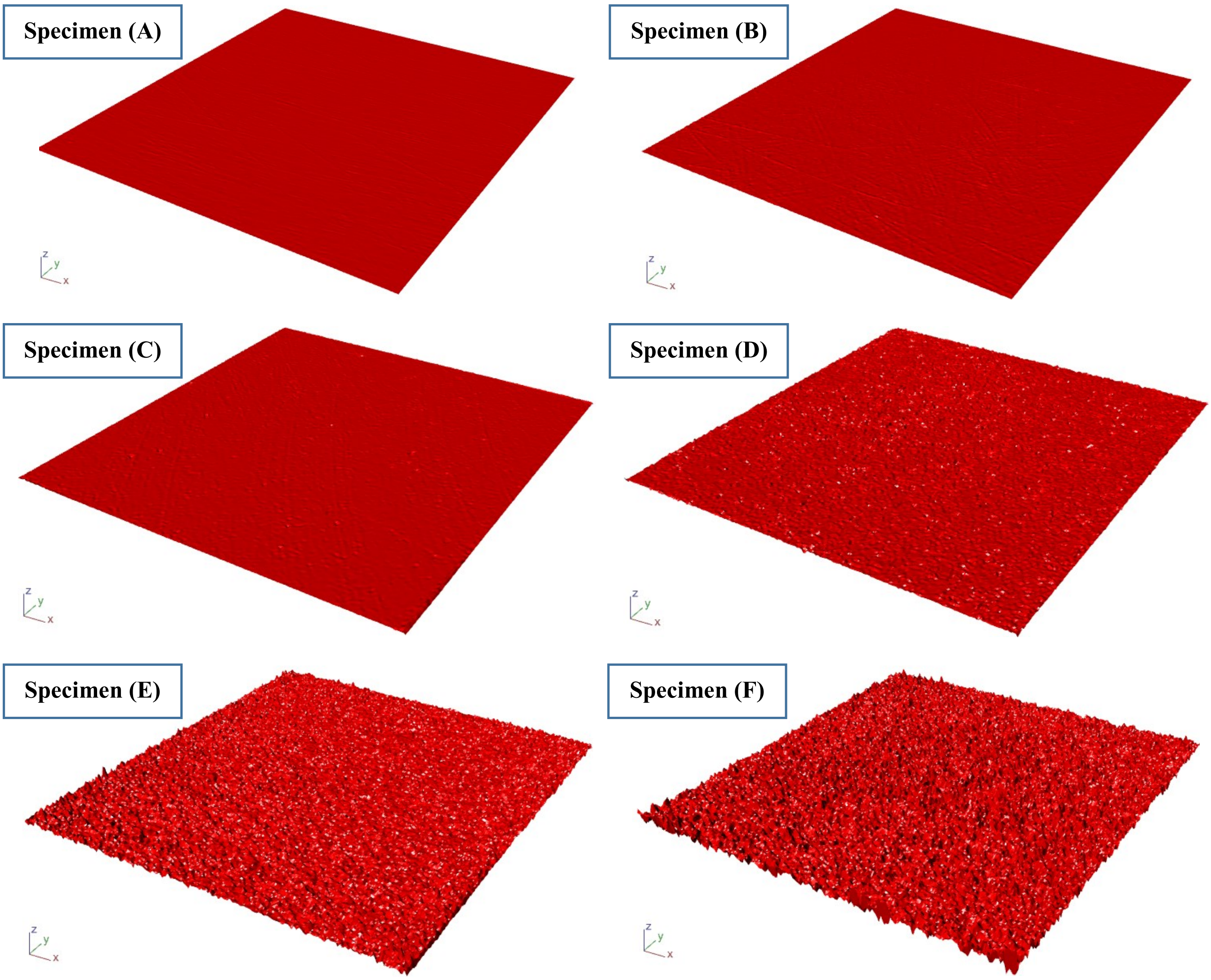

Figure 4: 3D modeling of Rubert gauge of all specimen

4 EXTRACTED DATA

The data extracted from the three-dimensional models of Rubert gauge's six specimens (A, B, C, D, E, and F) will be presented in two parts. The initial part will center on the outcomes concerning roughness parameters, specifically addressing the two-dimensional cross- sections comprising each specimen. The second part will involve the extraction of data related to the geometric features of the three-dimensional models.

4.1 Roughness parameters

The three-dimensional models designed for Rubert's six specimens were tested using the Gwyddion software. The Gwyddion is a popular open-source software used to extract amplitude roughness parameters and spacing roughness parameters from extracted data. In this study, both amplitude roughness parameters and spacing roughness parameters are analyzed based on the 2D roughness profile at the centerline section for each specimen. Figure 5 illustrates the 2D profile of specimen C at the centerline as an example.

The amplitude roughness parameters, as illustrated in Section 2.1, are calculated for Rubert's six specimens using Gwyddion. Table 1 displays the extracted data of the amplitude roughness parameters for all specimens. Figure 6 presents the waviness profile of specimen (F) along the centerline section.

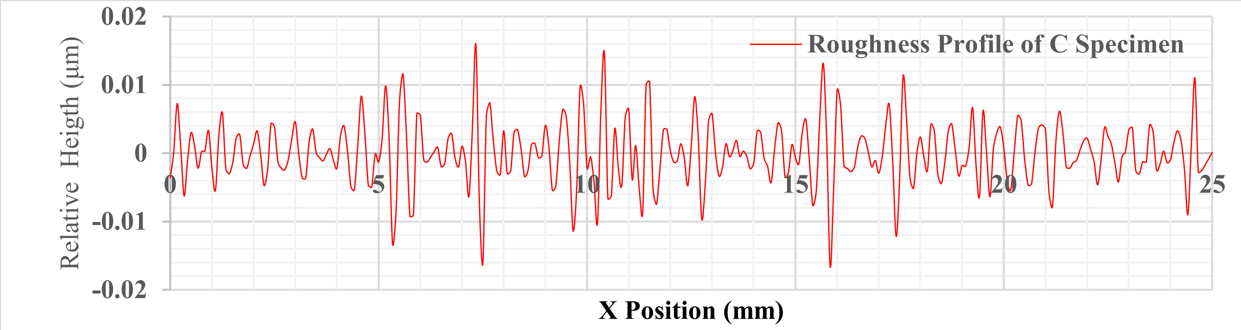

Figure 5: Roughness profile of specimen (C) at center line

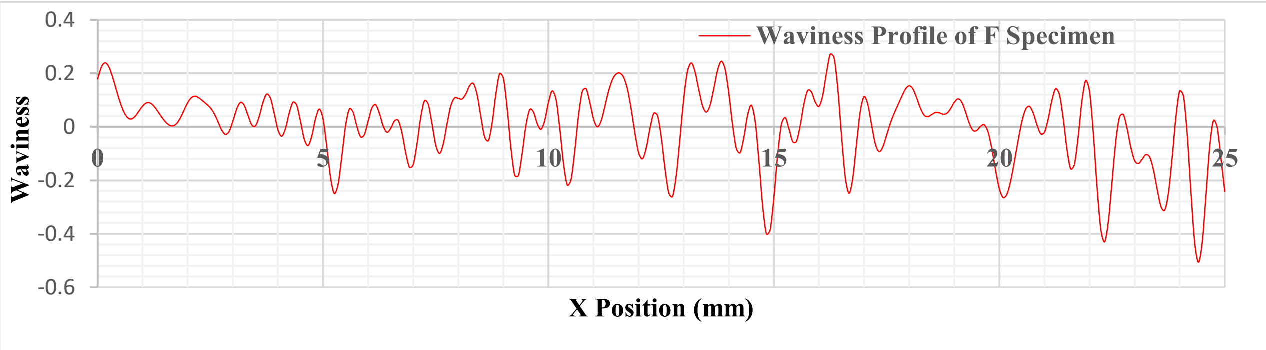

Figure 6: The waviness profile of specimen (F)

Table 1. The amplitude roughness parameter output of all specimen

Amplitude Roughness Parameter	Specimen Code					
	A	B	C	D	E	F
Roughness average (Ra) (µm)	0.0007	0.003	0.0034	0.016	0.028	0.056
Root mean square roughness (Rq) (µm)	0.0013	0.005	0.0046	0.023	0.038	0.073
Maximum height of the roughness (Rt) (µm)	0.02018	0.037	0.032	0.189	0.311	0.491
Maximum roughness valley depth (Rv) (µm)	0.0091	0.016	0.016	0.113	0.170	0.296
Maximum roughness peak height (Rp) (µm)	0.0110	0.020	0.015	0.076	0.140	0.195
Average maximum height of the roughness (R_{tm}) (µm)	0.0072	0.027	0.024	0.138	0.218	0.351
Average maximum roughness valley depth (R_{vm}) (µm)	0.003	0.012	0.011	0.079	0.124	0.183
Average maximum roughness peak height (Rpm) (µm)	0.003	0.014	0.012	0.059	0.094	0.16
Average maximum height of the profile (Rpz) (µm)	0.0091	0.031	0.027	0.151	0.235	0.400
Average maximum height of the roughness (Rz) (µm)	0.0072	0.027	0.0242	0.138	0.218	0.351
Maximum peak to valley roughness (R_{max}) (µm)	0.0201	0.034	0.031	0.188	0.311	0.470
Kurtosis (Rku) (-)	29.6952	5.28372	4.42218	6.55328	5.00509	3.91231
Skewness (Rsk) (-)	0.375	0.114	0.0026	-0.56	-0.31	-0.26

The spacing roughness parameters, which are illustrated in Table 2, are calculated for the 3D models of Rubert's six specimens. The calculations provide statistics on the count of peaks and valleys for each of Rubert's six specimen, along with their distribution on each individual slice. Figure 6 illustrates the relationship between the count of peaks and valleys and the relative height for each of Rubert's six specimen. It should be noted that the peak corresponds to positive relative height values, while valleys correspond to negative values. It is noticeable that specimen A, B, and C each contain peaks that are closely clustered within a narrow range, and their relative height values are very low. Hence, the three-dimensional models for these specimen appear like flat plate. As for specimen D, it contains many peaks with high relative height values. Regarding specimen E, it contains both peaks and valleys, but the valleys have high relative heights. As for specimen F, it contains peaks and valleys with high relative heights, and there is a similarity in the count between valleys and peaks. Figure 7 illustrates the 2D distribution of peaks and valleys on a slice for both specimen A and F along with their relative height.

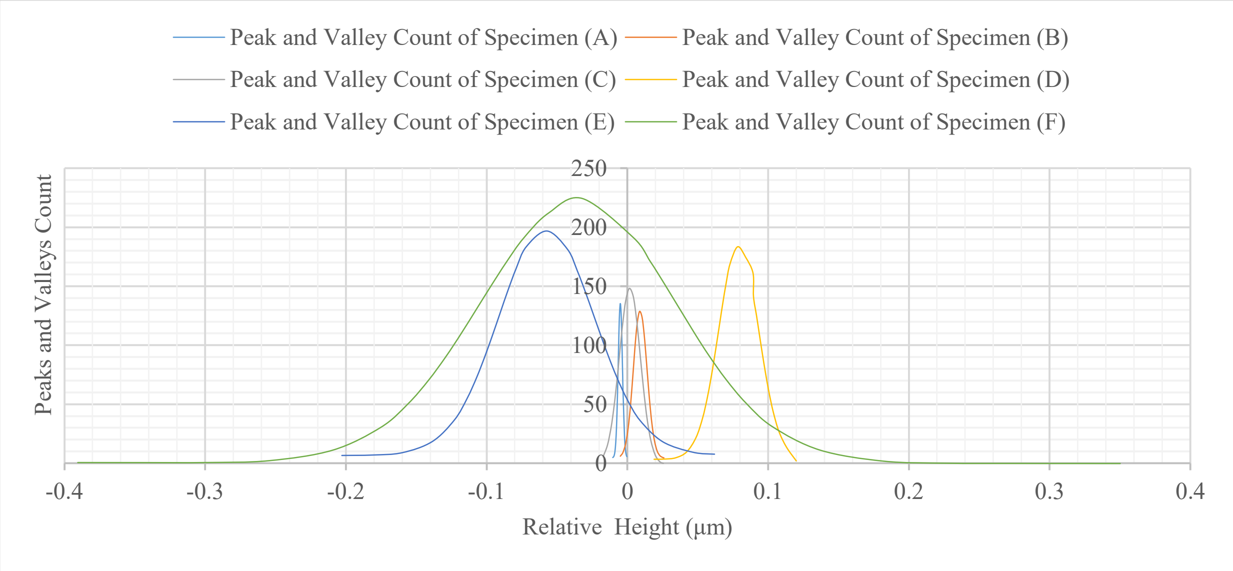

Figure 6: Peaks and valleys count of all specimen

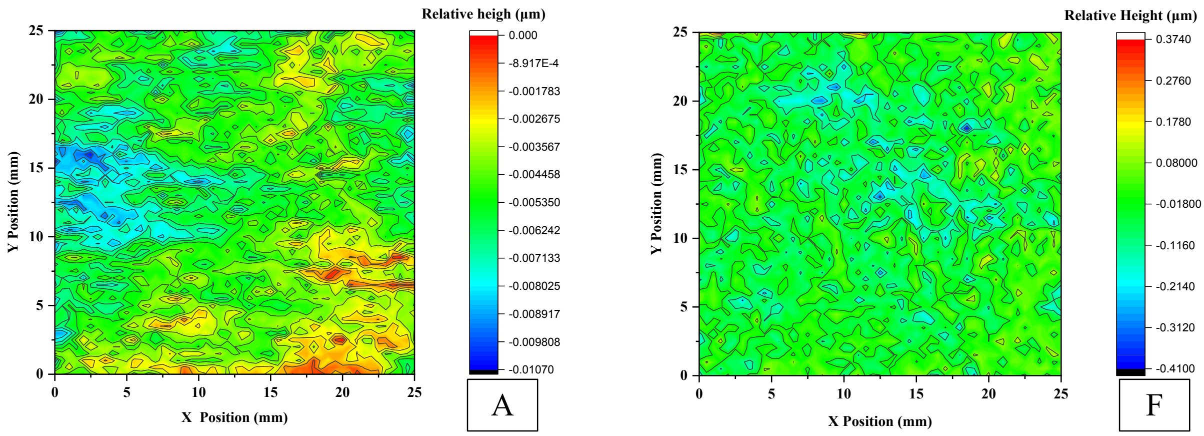

Figure 7: 2D distribution of peak and valleys heights for both specimens A and F

Table 2: The spacing roughness parameters of Rubert's specimens

The Spacing Roughness Parameters	Specimen Code					
	A	B	C	D	E	F
Number of pecks in profile (m)	197	174	137	125	88	54
Number of fluctuating points (g)	93	82	65	50	34	17

4.2 Geometric Features (GFs) Data

Three-dimensional models of Rubert gauge are utilized and tested using the CloudCompare software to generate geometric features (GFs). The CloudCompare is a free and open-source software for processing and analyzing 3D data, offering visualization, comparison, and various analysis tools. The CloudCompare software converts the full solid model to a 3D point cloud and extract the data of geometric features such as Omnivariance, Anisotropy, Surface Variation, Eigenentropy, and Verticality (Weinmann, 2017).

The calculated Omnivariance feature values of all Rubert gauge's specimens are shown in Figure 8. The results show that the Omnivariance of specimens A, B, and C falls within a narrow range, between 0 to 0.01. The Omnivariance value specific to the specimen (F) represents the higher value when compared to all specimens, approximately twice that of the specimen E. Figure 9 shows the calculated Eigenentropy feature values of all Rubert gauge's specimens.

The results indicate that the maximum value of the Eigenentropy is 0.04. All specimen A, B, and C exhibit a change in their Eigenentropy values, ranging approximately between 0.03 to 0.035. As for specimen D, E, and F, their Eigenentropy values vary between 0 to 0.04.

Figure 10 displays the calculated Surface Variation feature values for all Rubert gauge specimens. From the presented results, it is evident that specimens F possess the highest values in surface variation, while, conversely, specimen A exhibit the lowest values.

Figure 11 displays the calculated Verticality feature values for all Rubert gauge specimens. The verticality values for specimens A, B, C, and D lie within the range of 0 to 0.001, whereas spacemen F exhibits the highest value, measuring at 0.006.

Figure 12 displays the calculated Anisotropy feature values for all Rubert gauge specimens. It is noticeable that most of the Anisotropy values for all the specimen are close to one, while the specimen F exhibits variable values ranging from 0 to 0.99.

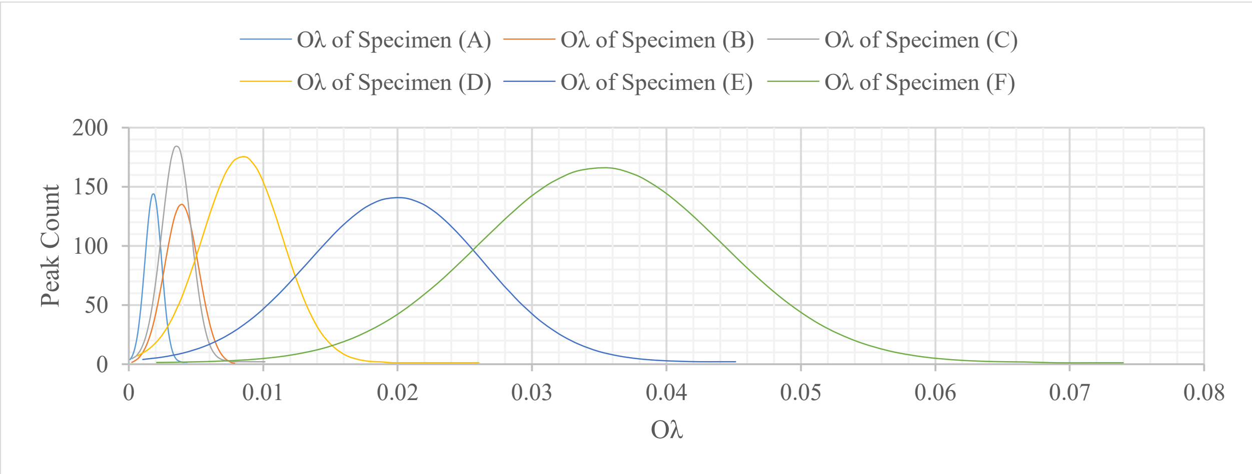

Figure 8: Omnivariance analysis for the six specimens of Rubert gauge

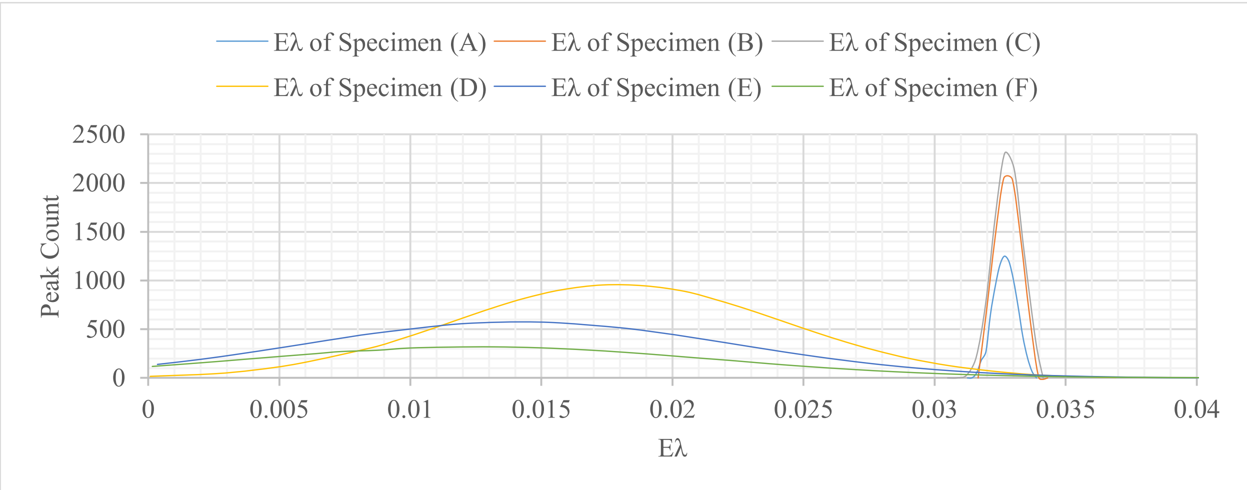

Figure 9: Eigenentropy analysis for the six specimens of Rubert gauge

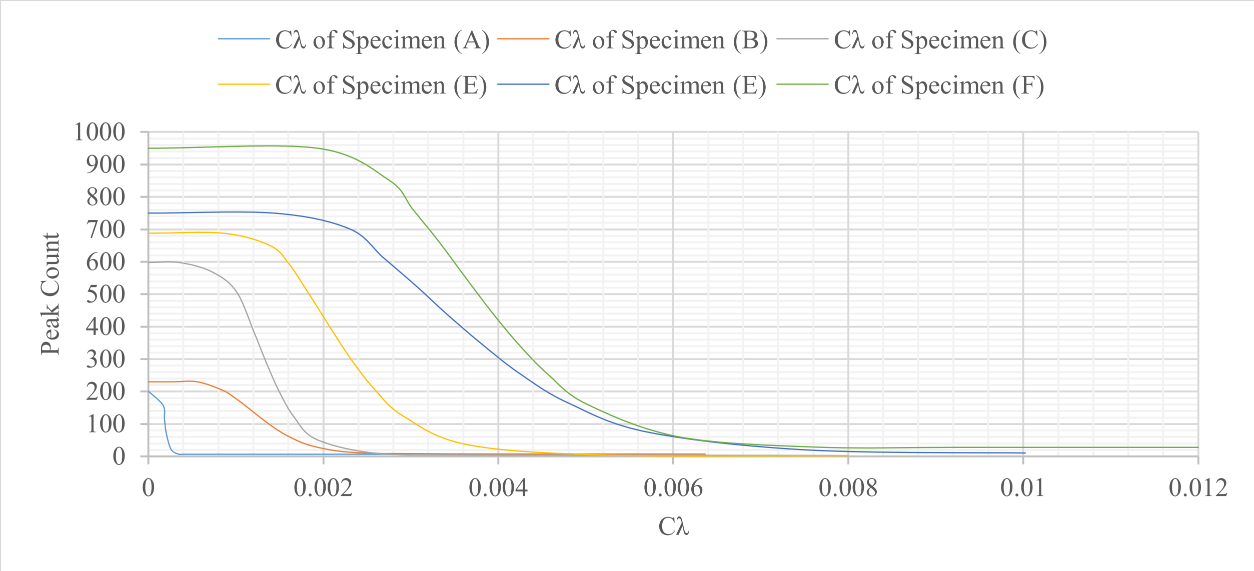

Figure 10: Surface variation analysis for the six specimens of Rubert gauge

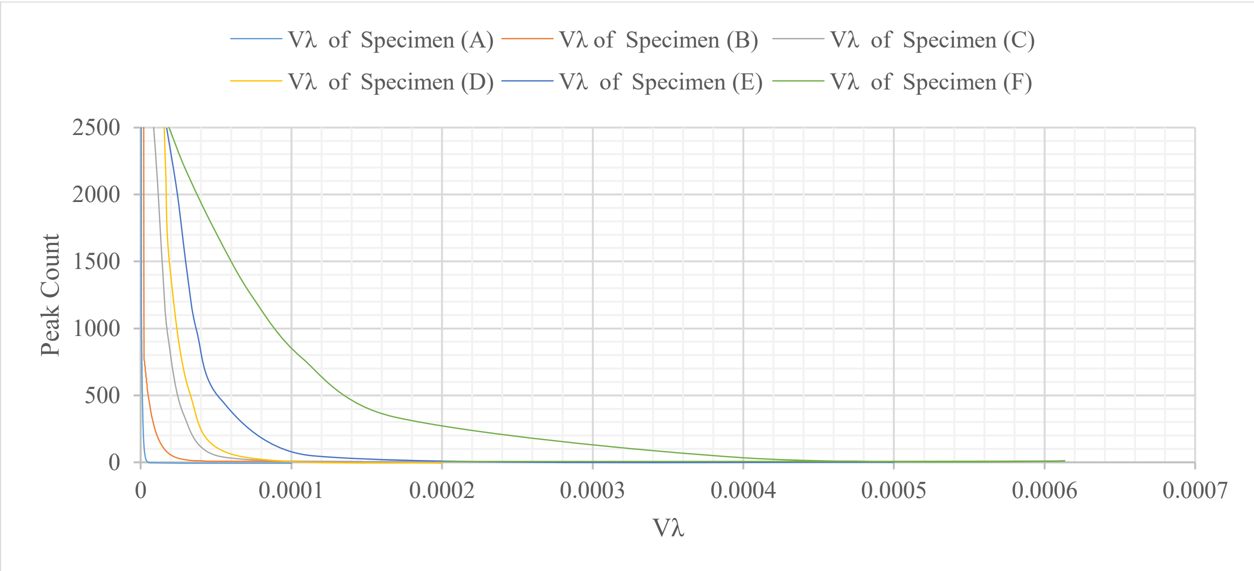

Figure 11: Verticality analysis for the six specimens of Rubert gauge

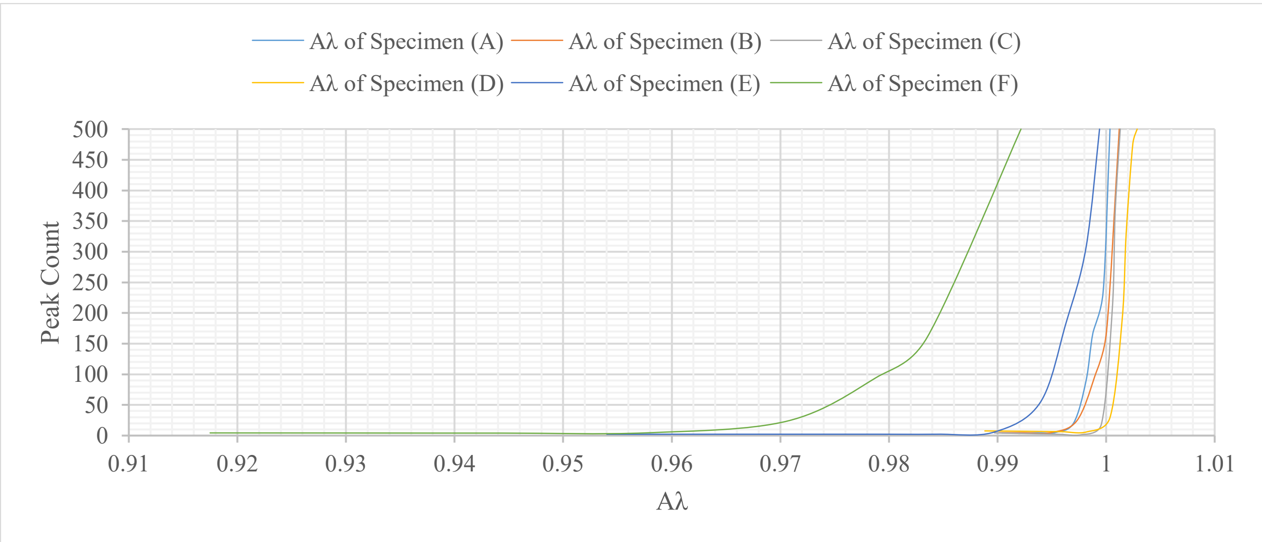

Figure 12: Anisotropy analysis for the six specimens of Rubert gauge

5 GRAPHICAL TOOL FOR PROPELLER SURFACE ROUGHNESS PREDICTION

5.1 3D Rubert Scale Equivalent Pro.

The extracted data, whether roughness parameters and geometric features, is utilized to construct a program. The program's objective is to determine the nearest three-dimensional surface of propeller blade to the six specimen surface of Rubert gauge. The program is built using classification algorithms, specifically the k-nearest neighbor's algorithm. This is done to classify the new surface data. It consists of roughness parameters and geometric features, and then compare it to the six specimen' data to identify the closest surface to the new one. The software architecture for this program is designed and developed using the MATLAB environment, through the App Designer code. The program is also used to calculate the power increase (ΔP) value for the new surface based on its roughness grade (Hussien M. 2023). This calculation relies on the equation provided for calculating the frictional sectional resistance of the propeller due to roughness, as mentioned in Section 2.2.

The program can create a plot illustrating the relationship between the number of propeller revolutions (rpm) and the power increase value. In addition, the program can also calculate the cost of polishing the propeller, depending on the input of propeller parameters such as its diameter (D), the number of blades (Z), blade area ratio (BAR) and the cost per square meter provided by the user for polishing. The graphical program is named "3D Rubert Scale Equivalent Pro.". Figure 13 illustrates the graphical user interface of the program, showcasing all its features, including the program's logo, input fields, and outputs.

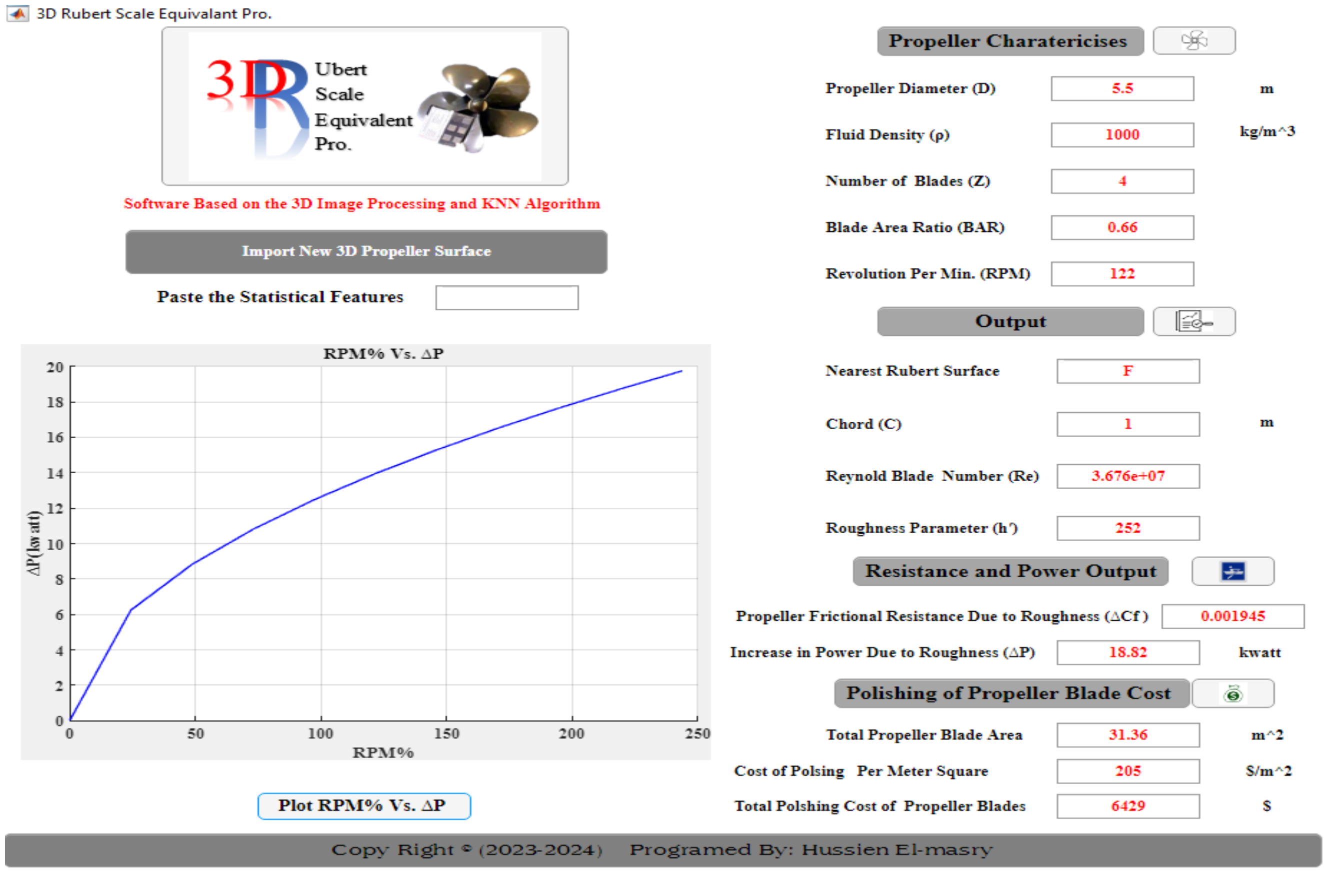

Figure 13: User interface of 3D Rubert scale equivalent pro.

5.2 Application: 3D Boat Propellers Analysis Program Verification

In this section, the objective is to implement the designed software for analyzing three-dimensional boat propellers. These propellers have been designed three times, maintaining consistent dimensions while varying the surface roughness. The complete design of the boat propeller is shown in Figure 14 and the three blades are visually represented in Figure 15. The essential dimensions and characteristics used as inputs for the program are as follows:

- Propeller Type: Conventional Propeller
- Propeller Diameter (D): 0.34 m
- Blade Area Ratio (BAR): 0.54
- Revolution per Minute (RPM): 800 r.p.m.
- Number of Blades (Z):3

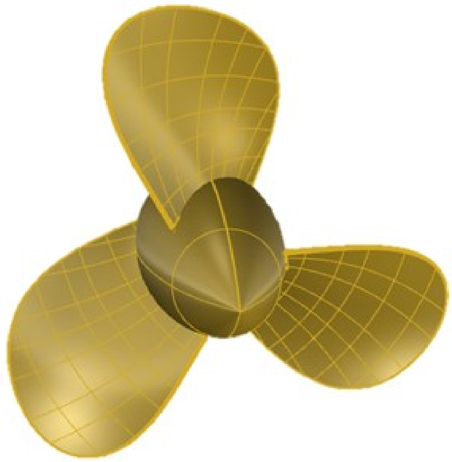

Figure 14: 3D Designed of full boat propeller

During program execution, calculations are performed for each blade's outputs, which are then presented in Table 3. Furthermore, the program establishes a relation between roughness parameter and power increase for each propeller, as shown in Figure 16.

Table 3: Output Data for different blade surface roughness as obtained from the program verification.

Blade Number	Nearest Rubert Surface	h' (µm)	10^3*ΔCF (-)	ΔP (kW)
Blade (1)	A	1.32	0.000109	0.273
Blade (2)	C	14.8	0.001246	1.32
Blade (3)	F	252	0.021250	4.86

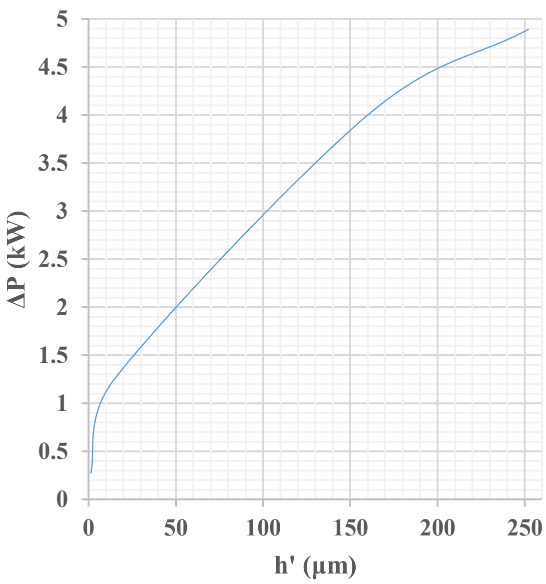

Figure 16: Program output Relation between roughness parameter (h') and power increase (ΔP) for designed blades

Blade (1) Blade (2) Blade (3)

Figure 15: Designed of three blades with different surface roughness

6 CONCLUSION

In conclusion, the development of the interactive program '3D Rubert Scale Equivalent Pro' has successfully addressed the challenge of calculating marine propeller roughness, grade, and value, which were previously undefined. By employing a multidisciplinary approach that encompassed 3D modeling, image processing, classification algorithms, and the analysis of various surface roughness parameters a robust solution for the marine industry have been achieved.

One key achievement of this paper is the creation of a 3D model for six specimens of Rubert gauge, which has been instrumental in determining the grade and value of marine propeller roughness. The three-dimensional models of each specimen were meticulously analyzed, and surface roughness data, including amplitude and spacing parameters, were extracted using the Gwyddion software. Furthermore, the extraction of geometric features data, such as Omnivariance, Anisotropy, Surface Variation, Eigenentropy, and Verticality, using the CloudCompare free software has added a valuable dimension to our analysis.

The heart of this paper lies in the development of the '3D Rubert Scale Equivalent Pro' software, which is equipped with a user-friendly graphical interface. This software, built using MATLAB App Designer, allows for the prediction of three-dimensional resistance values for marine propellers with previously undefined roughness characteristics. This prediction is facilitated through the application of a K-nearest neighbors (KNN) classification algorithm, which compares newly entered propeller data with information stored from the six specimens. This capability not only provides a powerful tool for propeller manufacturers and marine engineers but also contributes to the broader understanding of marine propeller design and performance.

In addition to software development, a rigorous verification process was conducted, with an example involving three-dimensional boat propeller analysis. This analysis included propellers with varying surface roughness while maintaining consistent dimensions. The program successfully calculated crucial data like roughness (h'), increased drag (ΔCF), and power increase (ΔP) for each blade. This verification process enhances the program reliability for real-world marine propeller performance.

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APPENDIXES

Appendix (1): The Amplitude roughness parameter

The Amplitude Roughness Parameter	Mathematical Definition
Arithmetic Average Height (Ra)	$R_a = \frac{1}{l}\int_0^l y(x)dx$
Root Mean Square Roughness (Rq)	$R_q = \sqrt{\frac{1}{l}\int_0^l y(x)^2 dx}$
Maximum Roughness Valley Depth (Rv)	$Rv = \|y_{min}\|$
Maximum Roughness Peak Height (Rp)	$Rp = y_{max}$
Average Maximum Height of the Roughness (R_{tm})	$R_{tm} = \frac{1}{N}\Sigma y_{imax}$
Average Maximum Roughness Valley Depth (R_{vm})	$R_{vm} = \frac{1}{N}\Sigma\|y_{i\,min}\|$
Average Maximum Roughness Peak Height (Rpm)	$Rpm = \frac{1}{N}\Sigma\|y_{i\,max}\|$
Average Maximum Height of the Roughness (Rz)	$Rz = \frac{1}{N}\Sigma y_{imax} - \frac{1}{N}\Sigma\|y_{imin}$
Kurtosis Coefficient (S_{ku})	$S_{ku} = \frac{1}{S_q^4}[\frac{1}{A}\iint Z^4(x,y)dxdy]$
Skweness (S_{SK})	$S_{SK} = \frac{1}{S_q^3}[\frac{1}{A}\iint Z^3(x,y)dxdy]$

Appendix (2): The Spacing parameter

The Spacing Roughness Parameters	Mathematical Definition
number of pecks in profile (m)	$m=\frac{1}{L}\sum_1^n m_i$
number of fluctuating points (g)	$g=\frac{1}{L}\sum_1^n g_i$

Appendix (3): The Geometric Features

The Geometric Features	Mathematical Definition
Omnivariance	$O_\lambda = \sqrt[3]{\frac{\lambda_1+\lambda_2+\lambda_3}{\lambda_3}}$
Anisotropy	$A_\lambda = \frac{\lambda_1-\lambda_3}{\lambda_1}$
Surface Variation	$C_\lambda = \frac{\lambda_3}{\lambda_1+\lambda_2+\lambda_3}$
Eigenentropy	$E_\lambda = -[\lambda_1\ln(\lambda_1) + \lambda_2\ln(\lambda_2) + \lambda_3\ln(\lambda_3)]$
Verticality	$V_\lambda = 1\text{-}nZ$