Quantitative assessment of increased frictional drag due to hull fouling using underwater surface scanning

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EXECUTIVE SUMMARY

The University of Melbourne and Franmarine Underwater Services Pty Ltd conducted an underwater scanning trial of a fouled ship hull for the purpose of determining the skin friction drag penalty due to biofouling. The trial was carried out at the Australian Maritime Complex in Henderson, WA. The 3D surface scanning was performed using AQUAMARS (Advanced Quality Underwater Mapping and Analysis for Rough Surfaces), a diver-operated device developed at the University of Melbourne. The vessel was scheduled for cleaning as the fouling growth was already significant.

The portside hull of Rio Tinto's tug boat (Uzmar Fleet Hull No: NB59) was scanned at 14 equally spaced locations along the length at a depth of one meter. In the future, additional measurement points could be taken from the hull (both portside and starboard) at various depths, or even on the propeller. However, the current trial provides sufficient data to demonstrate the scanning process and present the results of our full-scale drag prediction.

Comprehensive roughness statistics from the scanned locations are presented in this report. Overall, the aggregated equivalent sandgrain roughness of the surface is $\boldsymbol{k_{s,EHR} = 2.80}$ **mm**. This produces a predicted added skin friction of $\boldsymbol{\Delta \overline{C_f} = 125\%}$ or a predicted added total resistance of $\boldsymbol{\Delta R_T = 44.2\%}$ when cruising at 13 kn. These values are the difference from an ideal smooth hull. If the initial surface condition is known (e.g., from coating imperfections where some friction drag penalty is already expected), the increase in skin friction can be calculated relative to that condition.

The added cost of fuel and GHG emission are estimated for this case. To maintain a speed of 13 kn at the current fouling level, an extra cost of ∼**\$955/hr** would be required, and additional CO_2 emissions produced at the rate of ∼**1.3 T/hr**.

Key words: Biofouling, turbulent boundary layer; skin friction drag

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1. Introduction

The global maritime industry is acutely aware of the significant economic and environmental impacts of operating with roughened hulls due to marine biofouling. The increased drag and resistance result in tens of billions of dollars in extra fuel costs annually, not to mention the secondary costs related to health, emissions, and reduced operational efficiency. So why hasn't the industry taken stronger action? The problem lies in the unclear economic trade-off between the ongoing costs of excessive fuel consumption and the expenses associated with dry-docking. Hull cleaning decisions are often made based on fixed schedules, with the costs of cleaning (and potential operational downtime) being immediate and tangible. However, the long-term fuel penalty from rough hulls—though ultimately larger—remains uncertain. As a result, the industry often defaults to the conservative (yet wasteful) approach of bearing the cost of excess fuel consumption to delay cleaning and keep the vessel in service.

1.1. *Impact for Navy*

Roughness on underwater hulls and propellers—caused by factors such as the accumulation of calcareous deposits, biofouling (including biofilms and macrofouling), corrosion, and damage—is a common issue for both surface and subsurface Navy vessels. This roughness leads to a degradation in hydrodynamic and hydroacoustic performance. Schultz *et al.* (2011) estimated that light to moderate biofouling on the US Navy's DDG-51 class vessels costs around $1 Billion over 15 years. Considering that the DDG-51 class constitutes only about 0.1% of the approximately 119,000 vessels globally, it is clear that biofouling imposes a major economic burden.

Effective decisions on mitigating these effects depend on accurately quantifying hull roughness. Drag penalties do not scale linearly with roughness size. For example, just 50 μm of roughness can result in a 10% drag penalty, while 5 mm of roughness—an increase by two orders of magnitude—can lead to a 100% penalty. Drag prediction is therefore very sensitive to accuracy of roughness measurement, especially the small roughness elements. The first few tens of microns of roughness can disproportionately affect hydrodynamic drag and hydroacoustic performance. The Navy currently lacks the capability to make precise and economically informed decisions about roughness mitigation due to its inability to quantitatively assess the roughness itself. At present, roughness is assessed through qualitative visual and tactile diver surveys, which estimate: 1) biofouling coverage and its biological constituents, 2) the Rubert roughness of calcareous deposits on propellers, and 3) the extent of corrosion and damage. To improve decision-making, the Navy needs the ability to assess hull and propeller roughness with sub-millimeter accuracy. This data are inputs to existing and new models for predicting drag and hydroacoustic penalties.

2. AQUAMARS

Advanced Quality Underwater Mapping and Analysis for Rough Surfaces (AQUAMARS) is a 3D underwater hull scanner designed to map roughened surfaces on hulls, propellers, and underwater infrastructure. The TRL-5 (Beta Prototype) was developed by the team at University of Melbourne. The hardware features eight cameras that capture high-resolution images simultaneously when triggered by a diver. Using photogrammetry with specific calibration, we reconstruct a 3D surface of around 150×150 mm area. The reconstruction quality has been heavily bench-marked using known geometries and lab-quality laser scanning techniques. Both real-colour reconstruction and height maps will

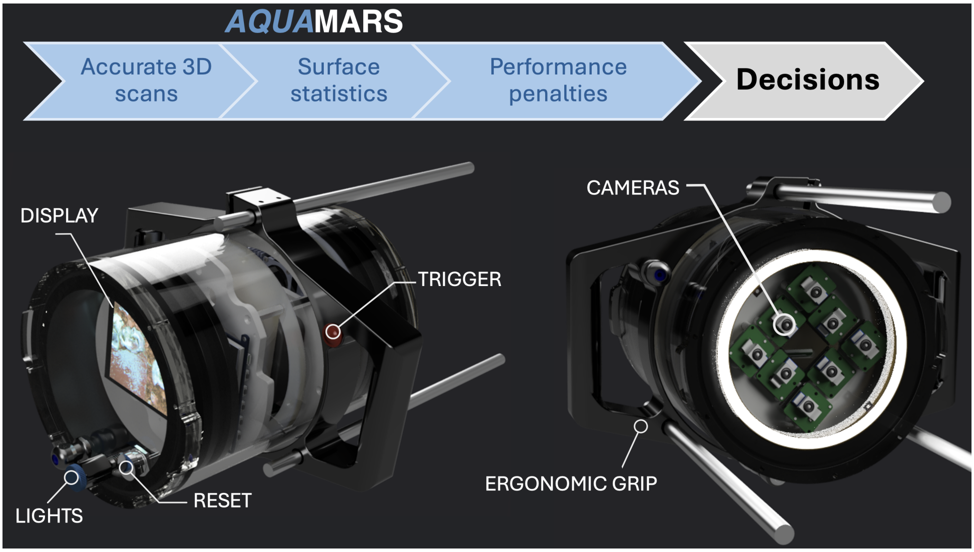

FIGURE 1. AQUAMARS and its use as a diagnostic and decision-making tools

Length [m]	Beam [m]	Draught max [m]	Cruise [m/s]	Full [m/s]	Operational zone
32	12.8	5.37	3.34	6.7	subtropical waters

TABLE 1. Ship parameters, cruise speed is assumed.

be produced. Furthermore, the device can be adjusted to scan above water such as during dry dock (before and after cleaning).

Operationally, a diver could scan 50-100 locations to account for the potentially uneven fouling. This will take around one hour. From this, a heat map of the hull could be produced for any roughness quantities, and to determine the aggregate value for the entire ship hull. There are several techniques to do this and this research is pioneered by UoM Fluid Mechanics Group (Hutchins *et al.* 2023).

AQUAMARS outperforms the existing methods (including underwater laser scan and sonar) providing high-quality spatial data crucial for assessing drag and performance penalties. This level of surface input is critical, particularly because higher order statistics and derivatives will be calculated from the data, as needed for drag prediction (Chung *et al.* 2021).

3. On-site measurement 2nd December 2024

The ship we measured in this trial is Uzmar (Hull No: NB59) and belongs to Rio Tinto (figure 2(a-b)). The scanned locations are shown in figure 2(c) on locations 1 to 14 for the portside. These locations were one meter below the waterline and are two meters apart in the length axis. It took less than 10 minutes to actually complete this line scan (excluding on-site adjustment at the dock).

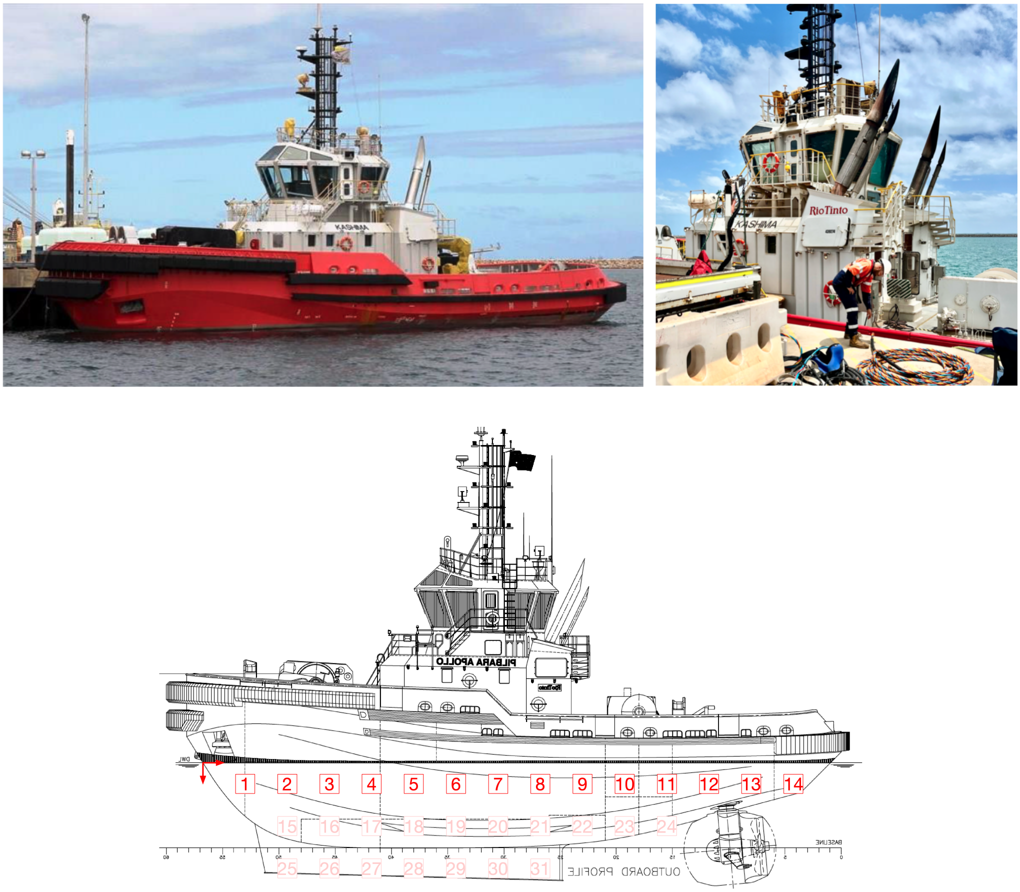

FIGURE 2. Uzmar tugboat examined in the trial. (a) Picture from specification; (b) photo from trial visit; (c) port-side schematic showing the scanned hull locations 1 - 14 and ideal scanned locations for future work 1 - 31

4. Results

4.1. *Hull scan and roughness parameters*

Hull roughness is commonly quantified during dry-docking using profilometer measurements of the peak-to-trough roughness height over a 50 mm traverse called Rt_{50} (Howell & Behrends 2006). This process is repeated at many locations over the hull of the vessel and the average hull roughness (AHR) is defined as the arithmetic mean of all observed Rt_{50}, which is used as input into hull drag penalty calculations. Figure 3 shows the heat map of AHR along the scanned locations. Since AQUAMARS produces area maps of hull locations, many '50-mm lines' can be included in every locations to obtain more converged values. From the limited number of scanned locations, there is no apparent trend in the AHR values from bow to stern (also agree with the photos, i.e. no significantly larger critters captured on either side). All the AHR values are shown in table 2. Location #12 did not reconstruct well so it is omitted from the data.

Note: Rt_{50} and AHR values have no physical meaning to the turbulent flow under the

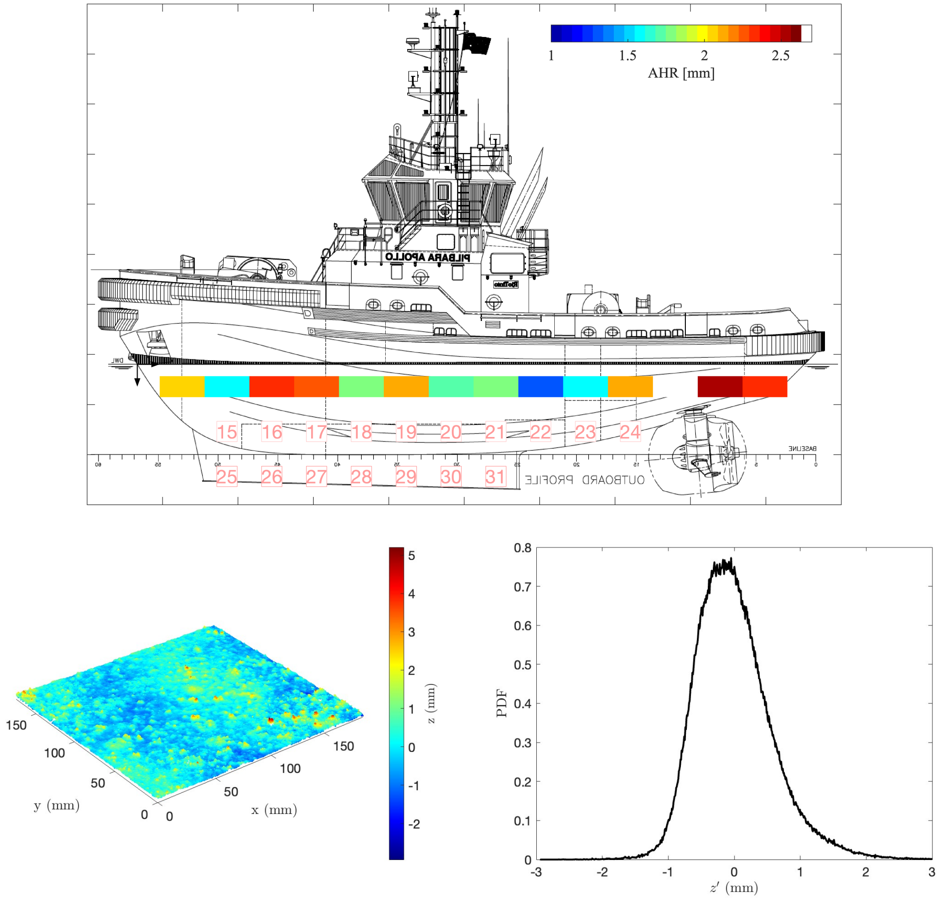

FIGURE 3. (a)Heat map of the AHR of the measured locations; example for location 1: (b) reconstructed topography and (c) height distribution.

hull and were defined simply for convention. Instead, for physics-based drag prediction, the correct roughness input is the 'equivalent sand grain roughness' or k_s.

4.2. *Equivalent sand grain roughness*

Equivalent sand grain roughness or k_s (Schlichting 1937) is a standardised parameter describing the roughness effect to the turbulent flows on any surface. It is NOT a physical measure of elevation, but the grain size on a hypothetical surface that would cause the same drag as the surface of interest (Bradshaw 2000). Hence, the actual value can only be determined from direct flow measurements, although there are models available with varying degrees of uncertainty. UoM is at the forefront of improving these models, optimising the balance between the parameters that are crucial for accurately capturing flow physics and the practical challenges of on-site measurement. As stated in Chung *et al.* (2021), the bare minimum surface parameters required for a good estimate of k_s are (a) some form of roughness height; (b) frontal solidity or effective slope; and (c) plan solidity, skewness or volume fraction. Heterogeneous clustering and directionality could also be important (if present) where this topic is an active research at UoM and elsewhere.

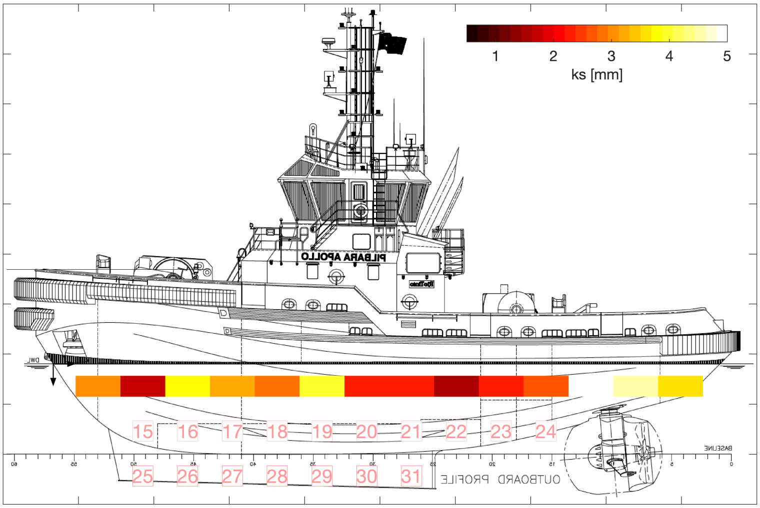

FIGURE 4. Heat map of the equivalent sand grain roughness k_s on the scanned locations

Figure 4 shows the heat map of k_s and table 2 the values. Here individual k_s was estimated using a method by Forooghi *et al.* (2017), however, the form was modified to eliminate the use of maximum peak-to-trough roughness height (k_t, not included here). This modification was made because k_t would be influenced by extreme asperities in real-world data, and, therefore, we do not recommend its use.
A new method developed at UoM (Hutchins *et al.* 2023) was used to average the varying values of k_s (as shown by the heat map and table) which takes into account patchiness or non-uniform distribution of roughness on ship hulls. This method is based on the power mean and the averaged value is $k_{s,EHR} = 2.80$ mm (termed *equivalent homogenous roughness*). This value will be incorporated into the full-scale drag prediction methods.

4.3. *Prediction of increase skin friction and total drag*

The total ship resistance coefficient comprises of residuary resistance (C_R) and frictional resistance (C_f), with the former mainly due to wavemaking hence is a function of Froude number. The correlation allowance (C_A) is included to account for pressure gradient due to hull shape. These inherent parameters are determined during the towing test in the vessel design phase. It is reasonable to assume that only skin friction coefficient will be altered by the biofouling growth, and the pressure drag of the hull form itself is not expected to be altered dramatically by the roughness (Schultz 2007).

Here we use a physics-based approach to calculate the friction drag increase due to the roughened hull. The method is based on the turbulent boundary layer evolution on a flat plate without pressure gradient (Monty *et al.* 2016). Recall the hull shape is accounted for by correlation allowance and less sensitive to surface roughness.

Figure 5 shows the ship's skin friction $\overline{C_f}$ curve as a function of Reynolds number Re_x. Multiple gray lines correspond to when the ship sails at different speeds. Indicated with the red marker are lines for cruise (6.5 kn) and full speed (13 kn). In those cases the skin friction drag increases by $\Delta\overline{C_f} \approx 105\%$ and 125%, respectively, defined as,

$$\Delta\overline{C_f} = \left.\frac{\Delta\overline{C_f}}{\overline{C_{fs}}}\right|_{Re_L} \times 100\% \tag{4.1}$$

Loc	k_{rms} [mm]	Sk [mm]	ES	AHR	k_s [mm]
1	0.675	0.797	0.261	2.035	3.078
2	0.460	0.421	0.235	1.564	1.627
3	0.642	1.053	0.321	2.322	3.766
4	0.614	0.813	0.319	2.230	3.276
5	0.544	1.209	0.252	1.800	2.788
6	0.648	1.730	0.265	2.112	4.016
7	0.486	0.974	0.241	1.721	2.225
8	0.544	0.652	0.260	1.795	2.320
9	0.406	0.661	0.207	1.300	1.450
10	0.498	0.973	0.247	1.587	2.322
11	0.586	0.720	0.281	2.100	2.739
12	-	-	-	-	-
13	0.744	1.017	0.351	2.511	4.594
14	0.632	1.081	0.309	2.347	3.634
				$k_{s,EHR} =$	2.801

TABLE 2. Roughness statistics for each measured location. $k_{s,EHR}$ is the aggregated sandgrain roughness for the entire hull following a method by Hutchins *et al.* (2023)

Length [m]	ν [m^{2}s^{-1}]	C_A	u_∞ [kn]	u_∞ [m/s]	Fr	Re_L	C_R/C_f	$\boldsymbol{\Delta\overline{C_f}}$ [%]	$\boldsymbol{\Delta R_T}$ [%]
32	0.81×10^{-6}	$\sim$0.0008	**6.5**	**3.34**	0.19	1.32×10^8	$\sim$0.63	105	64.5
32	0.81×10^{-6}	$\sim$0.0006	**13**	**6.7**	0.38	2.65×10^8	$\sim$1.83	125	44.2

TABLE 3. Ship hydrodynamic parameters. C_R/C_f is estimated from typical profile for Navy ships (Schultz 2007) unless provided by the ship builder. C_A is calculated from ITTC (1978).

For these two speeds, the increase in total ship resistance are $\Delta R_T \approx 65\%$ and 44%, respectively, where:

$$\Delta R_T = \frac{\Delta\overline{C_f}}{\overline{C}_{f,s}(1+\frac{C_R}{C_f}) + C_A} \times 100\% \tag{4.2}$$

Note that the percentage increase of ΔR_T is smaller for the full speed because the residuary resistance C_R from wave drag also increases. Here we use the C_R/C_f profile for a typical Navy ship (Schultz 2007), but can update this ratio if the towing test data (during design phase) is provided by the ship builder.

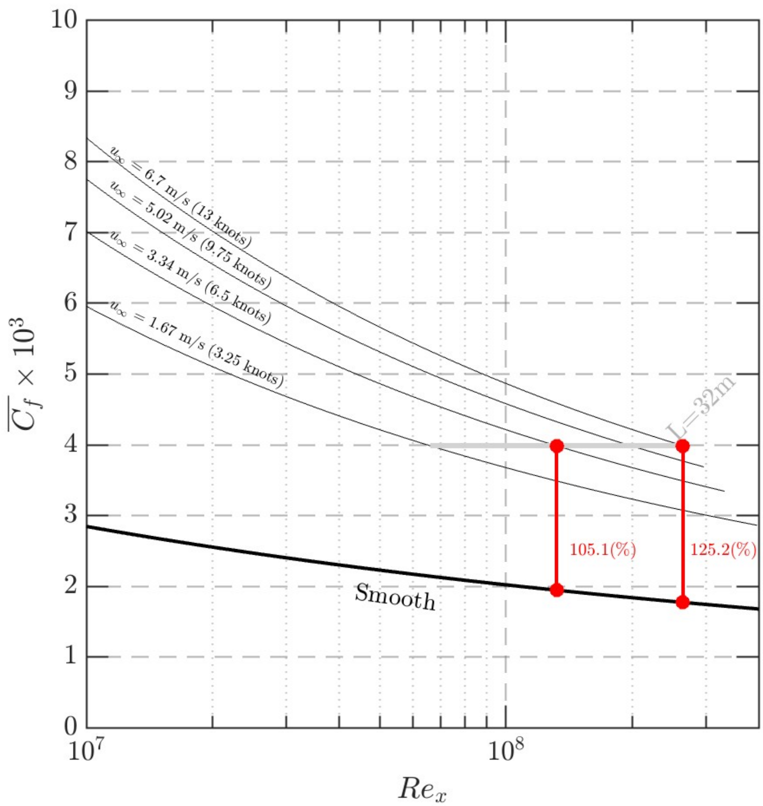

FIGURE 5. Average skin friction coefficient $\overline{C_f}$ against Reynolds number Re_x for the hydrodynamically-smooth surface (black line) and the current fouling level of the tugboat (gray lines), plotted for various speed.

u_∞ [kn]	Power required [kW]	efficiency [%]	fuel$_\epsilon$ [MJ/kg]	fuel$_\rho$ [kg/L]	fuel$_\$$ [\$/L]	fuel$_{CO_2}$ [kg$_{CO_2}$/kg]
13	4700	40	45.5	0.87	2.00	3.16

TABLE 4. Input for estimating fuel and cost penalties. Engine efficiency is assumed to be 40% for higher motor speed.

4.4. *Additional fuel expenditure and GHG emission for the current fouling level*

The potential fuel and cost penalties to maintain the full speed of $u_\infty = 13$ kn are calculated here. We only calculate this speed as the corresponding power required for lower speeds is not given. The input parameters are shown in table 4. As the increase in power is proportional to the increase in total resistance,

$$\Delta P = \overbrace{\Delta R}^{f(u_\infty^2)} \; u_\infty,$$

to maintain $u_\infty = 13$ kn one would need 44.2% more power, or an additional $\Delta P = 2077$ kW *(though engine power is not available in this case as full speed is evaluated).*

For baseline surface condition before fouling, the amount of diesel use is,

$$
\begin{aligned}
\text{Fuel use} &= \frac{\text{Power required}}{\text{efficiency}} \times \text{fuel}_\epsilon \\
&= 11.75 \text{ MW} \times \frac{1}{45.5 \text{ MJ/kg}} \\
&= 0.258 \text{ kg/s} \quad \text{or} \quad 929 \text{ kg/hr}
\end{aligned}
$$

Using marine diesel density and price in table 4, this corresponds to 1080 L/hr or \$2,160/hr to sail at full speed.

Therefore, with the current level of fouling, an increase of power required $\Delta P = 2077$ kW corresponds to an additional 410 kg/hr (or 477 L/hr) of diesel being burnt. The cost penalty to maintain full speed is therefore **\$955/hr**.

As 410 kg/hr more diesel is being burnt, the added GHG emission is

$$
\begin{aligned}
\Delta \text{CO}_2 \text{ emitted} &= \Delta \text{Fuel use} \times \text{fuel}_{\text{CO}_2} \\
&= 410 \text{ kg/hr} \times 3.16 \text{ kg}_{\text{CO}_2}/\text{kg} \\
&= 1298 \text{ kg}_{\text{CO}_2}/\text{hr}
\end{aligned}
$$

Hence, the added CO_2 emission to maintain full speed at this fouling rate is **~1.3 T/hr**.

5. Conclusion

We have demonstrated how AQUAMARS can be used to provide a quantitative measure of fouled underwater surface. Comprehensive surface statistics are key to properly estimate the roughness value, i.e., the equivalent sandgrain roughness k_s. From our scans, a heat map of k_s along the hull (or other quantities) can be produced. The image capture takes ~2 seconds per location, so the amount of time to do a full scan, adding moving time and preparation, can be estimated.

The aggregated equivalent sandgrain roughness of the observed hull is $\boldsymbol{k_{s,EHR} = 2.80}$ **mm**. This produces an added skin friction of $\boldsymbol{\Delta \overline{C_f} = 125\%}$ or an added total resistance of $\boldsymbol{\Delta R_T = 44.2\%}$ when cruising at 13 kn.

The added cost of fuel and GHG emission are estimated for this case. To maintain a speed of 13 kn at the current fouling level, an extra cost of **~\$955/hr** would be required, and unfortunately, additional CO_2 emission will be produced at the rate of **~1.3 T/hr**.

Further comments

(i) The drag increase was calculated from the hydrodynamically smooth baseline. Quantifying the initial surface condition after cleaning or coating (known to already produce some drag penalty) should be done to establish a more realistic baseline.

(ii) With scanning, the sigmoid biofouling growth rate can be properly tracked and plotted (including all the roughness parameters).

(iii) Future work can include scanning the propeller and establish the performance penalty.

(iv) For Navy purposes, elevated turbulent noise will occur due to roughness fouling. This will impact on sensor performance such as sonar and the effect can be diagnosed.

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