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Technical aspects of small autonomous surface vessel design

Abstract

Small unmanned, remotely operated or autonomous surface vessels are gaining popularity in the recent years, because of the increased need for automatization and cost reduction of activities such as environmental monitoring, collection of oceanographic data, surveillance and similar activities. Such vessels are powered by electricity stored in the batteries, which are heavy and relatively voluminous so, as in the case of bigger ships, there is a need for a proper vessel design which will minimise the resistance and consequently the consumption of the energy, while still being able to safely accomplish the required missions. Within the project Brigantine (Interreg HR-IT), a small vessel having a length of 2.2 meters, and denominated as ASV02, is designed for the coastal and open sea missions. This paper describes the challenges of the development of the concept and the design of the prototype, as well as the operational requirements. In addition, the paper describes the technical details related to the production of the prototype and presents a new propeller characteristics prediction method useful when there is barely any data available.

Keywords: autonomous vessel, vessel design, hull form, hydrodynamic resistance, propeller characteristics

1. Introduction

Small uncrewed, autonomous, or remotely operated surface vessels (ASVs) have been gaining popularity in recent years due to various factors, ranging from the availability of technological solutions to the need for cost reduction and automation of activities related to environmental protection, surveillance, and other tasks that can be performed without the need for a human operator onboard. This trend is further supported by the development of affordable and application-specific small ASVs for mapping, monitoring, and environmental data collection (Raber and Schill, 2019; Setiawan et al., 2022; Sotelo-Torres et al., 2023). Recent work has also focused on enhancing autonomy through improved sensor integration and communication design (Schreiter et al., 2024). Similar trends are observed in numerous recent studies focusing on design optimization, autonomy, and control of small USVs and ASVs (Kolev et al., 2021; Li et al., 2019; Xiros et al., 2024).

Within the context of this paper, a small vessel refers to vessels with a length not exceeding five meters, typically much smaller. Bolbot et al. (2023) identified 84 very small vessels with a displacement of less than 100 kg, listing their owners, operational areas, scopes, as well as type, size, and weight. Similar efforts to classify and experimentally evaluate small-scale USVs can be found in the works of Rybin et al. (2020) and Wajs and Kasza (2021), who focused on autonomy range and low-cost bathymetric platforms respectively. It should be noted that research groups developing autonomous vessels belong to a very small number of countries. The USA and China had the highest numbers of vessels identified by Bolbot et al. (2023), 14 and 12 respectively, while only one vessel was identified in Croatia, owned by the LABUST research group of the University of Zagreb Faculty of Electrical Engineering and Computing.

The design, equipping, and production of small vessels is not a straightforward task, and research is required at all stages of development. Yang et al. (2024) evaluated the technologies, motion models, and algorithms required for enabling autonomous navigation in existing small ships. Roasto et al. (2021) considered the design and testing of universal ASV. Emilolorun and Singh (2024) described the development of a Low-Cost Unmanned Surface Vessel for Autonomous Navigation in Shallow Water. Chaysri et al. (2024) proposed the design and implementation of an ultra low-cost (under 1000 euro) surface vessel, using a kayak as a carrier for equipment while Gilboa (2022) confirmed that affordability can be achieved without sacrificing functionality in coastal monitoring missions. Other researchers focused on specific design challenges, from power system efficiency (Sohn et al., 2015; Elkolali et al., 2020) to modular hybrid architectures integrating USV and ROV systems (Jung et al., 2018; Sarda and Dhanak, 2016).

While using an existing hull can be useful for different purposes, designing a hull from scratch can be challenging for various reasons, such as a lack of experience, high sensitivity to mass distribution, resistance estimation, and propulsion design,

since most well-established methods for larger ships are of questionable applicability to small ASVs. Ghazali et al. (2024) made a review of the unmanned surface vehicles from a hull design perspective, concluding that hull design stands as a crucial stage in ASV development, as it dictates the payload capacity and its dynamics characteristics.

This paper adds to the state-of-the-art research on successful hull design of small ASVs. It presents the design considerations and solutions for building ASV02 vessel within the scope of Interreg HR-IT project “Chemico-physical and multispectral Data fusion for Adriatic Sea monitoring by autonomous vessel – BRIGANTINE”. This paper is organized as follows:

- ◇ **Operational requirements:** Defines the main functional, dimensional, and regulatory constraints that guided the ASV02 design, such as vessel length, transportability, and mission versatility.
- ◇ **Hull form requirements:** Describes the hydrodynamic and structural parameters influencing hull geometry, including freeboard height, propeller protection, slenderness, and beam limitations.
- ◇ **Concept variations:** Presents several alternative hull concepts with different displacements and form characteristics, analysing their advantages and drawbacks in terms of stability, performance, and producibility.
- ◇ **Resistance prediction:** Provides hydrodynamic resistance estimates based on the Holtrop method and assesses power requirements for different operational speeds and displacements.
- ◇ **Propeller choice:** Presents criteria for a propeller type selection and a propulsive characteristics estimation for the chosen propeller.
- ◇ **Final concept:** Summarizes the finalized hull geometry and construction adjustments, including modifications to length, keel design, and propulsion integration.
- ◇ **Conclusion:** Synthesizes the design outcomes, discusses performance expectations, and outlines future steps including testing, optimization, and integration of autonomous control systems.

2. Operational requirements

Design of the BRIGANTINE ASV02 vessel started with the definition of the operational requirements. The first requirement is that the vessel length is below 2.5 meters, due to the legal requirement in Croatia that vessels above 2.5 meters should be officially registered. The main vessel concept was determined by the requirement that the transport and manipulation of the vessel must be as easy as possible. The ASV02 shall therefore be a catamaran so that, when disassembled, it can be transported on the roof of a car. The initial rough estimate of the weight of both hulls was about 30 kg, which fits within the typical car roof load limit.

Following the expert discussion, the following was decided:

- ◇ ASV02 shall be able to perform different missions, optimally for the project, but also for the upcoming follow-up and other future projects.
- ◇ The main engines should be outside of the ship (as opposed to the in-hull engine placement).
- ◇ Classic two-propeller solution will be installed (as opposed to the podded single-engine solution, two podded engines solution, and classic two-propeller solution with rudders).

3. Hull form requirements

Hull form requirements resulted from operational requirements and the ability to carry submerged oceanographic equipment. Therefore, additional requirements were set during the design process:

1. Sufficient height above the water
 - ◇ The deck and bridge equipment should get splashed as little as possible when sailing on waves.
 - ◇ The boat is too small not to get splashed at all.
 - ◇ The choice should provide sufficient splash protection in average operating environment.
 - ◇ A height of 30 cm above the water was chosen, with the possibility of adjustment in the final design of ASV02.
2. Protection of the propeller
 - ◇ The propeller should be protected against impacts with objects during missions or during transport and maintenance.
 - ◇ Various protection ideas were discussed and are described in Concept variations chapter.
3. Slender body design
 - ◇ Slender bodied hulls reduce the resistance and provide calmer sailing through waves.
 - ◇ ASV02 is long enough and hull beam requirement low enough to make slender body design possible.
 - ◇ The required sailing speed is at the top of attainable speeds in displacement mode and slender body makes reaching that speed possible without going into semi-displacement or planing mode.
4. Hull beam large enough to easily place batteries inside.
 - ◇ A maximum beam of 30 cm was chosen based on battery dimension
 - ◇ Possibility to narrow it down to 25 cm depending on the final boat weight.
5. Transom wide enough to protect the propeller
 - ◇ When berthing, the point of first contact with a quay should be the deck and not any part of the propeller.

- ◇ Transom itself could be even narrower but then the propeller would “stick out” of stern in top plane view and would become unprotected.

4. Concept variations

Uncertainty in the masses of some components led to the exploration of several displacements. Initially the displacement of 90 kg was considered, and similar concepts were made for 70 kg displacement. With the development of the project, a heavier displacement became more likely. Therefore, final concepts were considered at 100 kg.

A displacement, sailboat-like hull was used in most concepts. Gentle waterline curvature of this type of hull should result in low resistance and smooth sailing. The side slope on some concepts protects the side and makes the deck the first to contact the quay. The keel was initially a long straight girder since it offered propeller protection when sailing forward and laying the boat on flat ground would be easy. Such keel would also provide good course keeping. Eventually, that keel was abandoned, and a curved keel was adopted since it offered more harmonic stern waterlines.



Figure 1. One of abandoned concepts with long straight keel.

4.1. Concept 03b-70

Concept 03 was developed more thoroughly than previous concepts (not mentioned in this paper). A skeg was added for course keeping and propeller protection. The stem is almost vertical to make a hull form that would cut through waves rather than to climb on them. The beam of the hull was scaled down to 250 mm which made the sides more vertical. A transom had to be relatively wide to make the stern wider than the propeller. Only 70 kg version was made. Afterwards it was decided to do a concept with 100 kg displacement since it is more likely that this would be the displacement of fully equipped boat.

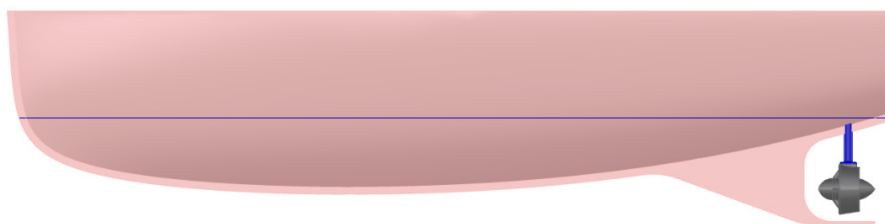


Figure 2. Concept 03b-70, $L = 2500$ mm, $B = 250$ mm, $D = 300$ mm, $F = 300$ mm.

4.2. Concept 06a-100

Last concept in the initial design period ended up having less vertical stem and lowered transom. The longitudinal centre of buoyancy of previous concept was too far forward and that was the reason for the change. It was shortened to 2.4 m to allow for small add-ons to the hull while keeping LOA under 2.5 m, Figure 3. The aft part of the waterline is very moderately angled to the centerline to make the water flow as smoothly as possible. The longitudinal centre of buoyancy was pushed aft even though the transom had been narrowed. As a final concept, producibility was emphasized, so fillets were added, the transom was given a 5° angle, and the skeg was made optional rather than an integral part of the hull form. The draft mentioned is with skeg included. Without a skeg, it would be close to 250 mm.



Figure 3. Concept 06a-100, $L = 2400$ mm, $B = 300$ mm, $D = 300$ mm, $F = 300$ mm.

The performance of the concept was explored to obtain data for rational decisions on the power consumption of the ASV02 and the corresponding number and weight of batteries. Only the fully loaded boat was considered. Lower weights will result in lower power consumption and increased range. Hull centrelines are 955 mm apart. If needed, they might be put closer together or wider apart. Hydrostatic data were calculated for 100 kg displacement on even keel, Table 1.

Table 1. Hydrostatic data.

Load Condition Parameters	
Weight [kgf]	100
Longitudinal Centre of Gravity, LCG [mm]	1227
Vertical Centre of Gravity, VCG [mm]	300
Fluid Type	Seawater
Fluid Density [kg /m ³]	1025.9
Resultant Model Attitude	
Heel Angle [°]	0
Trim Angle [°]	0
Sinkage [mm]	0.269
Overall Dimensions	
Length Overall, LOA [mm]	2390
Beam Overall, BOA [mm]	1254
Depth Overall, D [mm]	551
Waterline Dimensions	
Waterline Length, LWL [mm]	2261
Waterline Beam, BWL [mm]	1200
Navigational Draft, T [mm]	252
Volumetric Values	
Volume [m ³]	0.097
Longitudinal Centre of Buoyancy, LCB [mm]	1227
Vertical Centre of Buoyancy, VCB [mm]	-78
Wetted Surface Area [m ²]	1.961
Moment to trim	0.83
Water plane Values	
Area [m ²]	0.787
Longitudinal Centre of Floatation, LCF [mm]	1291
Weight to immerse [kgf/cm]	8.073
Sectional parameters	
Maximum Section Area, Ax [m ²]	0.074
Longitudinal Ax location [mm]	1184

Hull form coefficients	
Block Coefficient, C_b [-]	0.142
Prismatic Coefficient, C_p [-]	0.584
Maximum Section Coefficient, C_x [-]	0.244
Waterplane Area Coefficient, C_{wp} [-]	0.290
Wetted Surface Coefficient, C_{ws} [-]	4.178
Static stability parameters	
Transversal Moment of Inertia, I_t [m ⁴]	0.182
Transversal Metacentric Radius, BM_t [mm]	1869
Transversal Metacentric Height, GM_t [mm]	1490
Longitudinal Moment of Inertia, I_l [m ⁴]	0.22
Longitudinal Metacentric Radius, BM_l [mm]	2254
Longitudinal Metacentric Height, GM_l [mm]	1876

4.2.1. Concept 06a-100-Resistance prediction

Resistance prediction was done using the Holtrop method, which was assessed to be the fastest and sufficiently reliable for this type of hull, although the B/T ratio is outside the recommended values for the method. The data used for the calculation are presented in Table 2.

Table 2. Input data for resistance prediction.

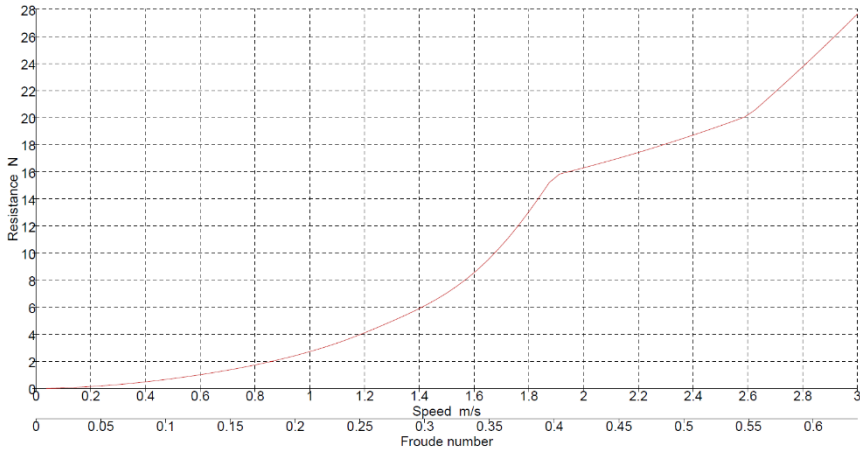
Waterline Length, LWL	2.283	m
Beam	0.246	m
Draft	0.24	m
Displaced volume	0.048	m ³
Wetted area	0.911	m ²
Prismatic coeff. (C_p)	0.576	
Waterpl. area coeff. (C_{wp})	0.701	
1/2 angle of entrance	10	deg.
LCG from midships	0.007	m
Max sectional area	0.037	m ²
Deadrise at 50% LWL	52.9	deg.
Hard chine or Round bilge	Round bilge	
Correlation allowance	0.0004	
Kinematic viscosity	1.19E-06	m ² /s

The resistance calculated is the bare single hull resistance force while the power is calculated with a design margin of 25%. Since each hull has its own propeller the effective thrust power of each propeller is taken to be equal to the calculated one for the single bare hull. The design margin is expected to cover the appendages (mostly submerged measuring equipment) and hull interference. The results are presented in the following Table 3. and a pair of diagrams, Figure 4a and b. It is expected that each propeller would need to provide approximately 40 W thrust power for the boat to sail at 2 m/s on still water.

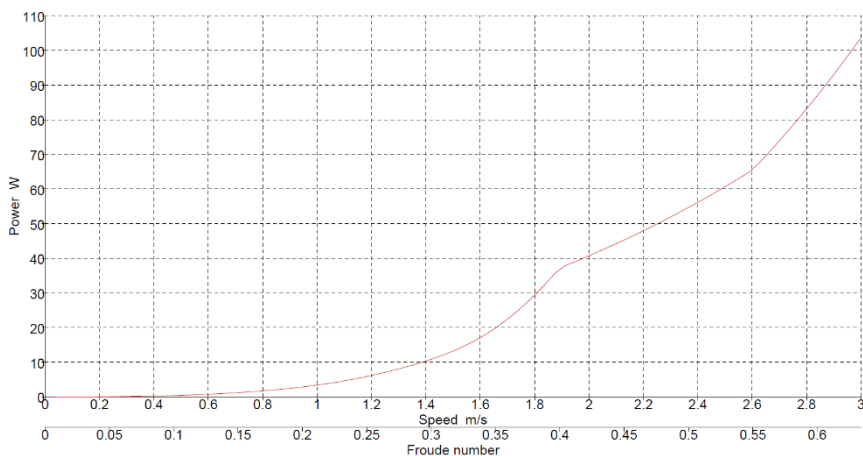
Table 3. Resistance prediction results.

Speed (m/s)	F_N	R N	P_E W
0.0	0.000	0.00	0.00
0.2	0.042	0.14	0.04
0.4	0.085	0.49	0.24
0.6	0.127	1.02	0.76
0.8	0.169	1.74	1.74
1.0	0.211	2.72	3.40
1.2	0.254	4.11	6.17
1.4	0.296	5.90	10.33

Speed (m/s)	F_N	R N	P_E W
1.6	0.338	8.55	17.09
1.8	0.380	13.05	29.36
2.0	0.423	16.29	40.73
2.2	0.465	17.43	47.93
2.4	0.507	18.71	56.13
2.6	0.549	20.13	65.43
2.8	0.592	23.75	83.11



(a)



(b)

Figure 4. Resistance prediction diagram: (a) force, (b) power.

The results weren't experimentally validated at the time of publishing this paper. Boat's sea trials, planned to take place at later phases of the project, will provide an information on applicability of the method and needed corrections.

5. Propeller choice

5.1. Regular procedure

When designing a propeller for a particular ship, the optimum propeller for a particular speed and function is sought. One of the most important factors for a quality propeller selection is knowledge of its thrust and torque characteristics for various combinations of forward and rotational speeds and diameters. For larger propellers intended for boats and manned ships, the data is generally available. On the other hand, manufacturers of small propellers intended for model vessels and small unmanned vessels do not provide sufficient data. When designing, we are limited to the bollard pull characteristics with the delivered power and the associated torque unknown or only partially given.

In such conditions, it is not possible to accurately predict the degree of suitability of a propeller for a particular hull and its function. Regardless, it is possible to assess with a certain degree of certainty which of the offered propellers would be the best option based on similar propellers with known characteristics, engineering practice, and empirical data.

5.2. Design requirements

The vessel must achieve a speed of 2 m/s when moving forward on calm water with the lowest possible consumption of electricity. The propeller must also be suitable for lower rotational propeller speeds and forward speeds of the vessel, but it does not have to have optimal efficiency. It must be possible to drive in reverse by changing the direction of rotation, but the vessel does not have to achieve the same speed as when moving forward. It is necessary to prevent seaweed from wrapping around the propeller. It is also desirable that the propeller is protected from impacts, whether during navigation or when handling the vessel on dry land.

5.3. Possible topologies

A propeller with regular geometry is the simplest to design. Numerous series of such propellers have been tested, and it is likely that this type of propeller would also be the most efficient of all the topologies considered. Such propellers are less resistant to seaweed entanglement and do not have any protection against impacts with objects. They can be protected by additions to the shape such as a skeg in front of and below the propeller.

Skewed propellers are more resistant to entanglement of seaweed that is cut or slides on the sloped leading edge of the blades. They are not as efficient as regular propellers and are more difficult to manufacture. Less information is available on the characteristics of such propellers.

Ducts on ducted propellers are strong enough to protect the propeller from impacts, and they also allow for add-ons (like a net on the leading edge) to protect against seaweed. Data on tests of such propellers are available, but the amount is significantly lower than that of regular propellers. Those propellers are less efficient at higher speeds since the duct then causes greater resistance, although it still contributes to improving the flow on the propeller.

Ducted hubless propellers offer similar advantages to regular ducted propellers with an additional reduction in propeller drag due to the absence of a hub, which does not provide any propulsion effect anyway but only serves as a support for the blades. The disadvantage is that the duct is even thicker and causes more drag at higher speeds than a regular duct.

5.4. Propeller thrust characteristic

Thrust curves (K_T vs. J) of similar propellers are close to being parallel. This parallelism allows us to derive an equivalent curve for any propeller by knowing only one point on the curve. For available propellers, this point is the bollard pull thrust, or the thrust force (T) when the forward speed (v_a) is zero. Since the manufacturers

also provide rotational speed and the diameter of the propeller at that point, the thrust coefficient is then calculated as:

$$K_T = \frac{T}{\rho n^2 D^4} \quad (1)$$

where T is a thrust force [N], ρ is a fluid density [kg/m³], n is a rotational speed [1/s] and D is a diameter [m].

With the thrust coefficient at zero forward speed known, we can place the starting point of the K_T curve and draw the curve through that point parallel to the other curves. The procedure above could also be done with ducted propellers. K_T curve topology is a bit different and more complex, but parallelism still exists, and a reasonable approximation can be derived.

5.5. Propeller torque characteristics and efficiency

Similar procedure would have been applied for torque prediction but there was no such point available for the torque diagram. Being unable to acquire any propeller torque data to make a similar approximation as with thrust force, a propeller efficiency was conservatively approximated, and the torque was derived from it. This is the weakest point of the propeller choice procedure because of the large error margin that could lead to unnecessary overpowering of the vessel, but underpowering was not acceptable since the boat wouldn't be able to reach the required speed.

5.6. Propeller selection

Propeller efficiency would be the most important factor in propeller selection if it were not for the lack of thrust/torque data. This way, with all calculation insecurities, other factors became more important than they would normally be.

Propellers with more operational data available were favoured. Ready-made propeller/motor combinations were considered better than separated components since they were already tested for compatibility and propeller characteristics refer to exact configuration. That way the number of unknowns and unexpected problems in the design process is reduced. Ease and reliability of purchase were important since there is small time margin available inside the project for resolving potential problems with delivery and return.

Final choice came down to one Blue Robotics configuration. Besides the factors mentioned in the previous paragraph, project partners satisfactory experience with the components and support from the manufacturer played a role as well.

The configuration will require more battery power than the smaller one but the risk of underpowering is eliminated. And if the trial tests show that the vessel is overpowered then the battery capacity could be reduced resulting in a lighter vessel.



Figure 5. Blue Robotics T500 thruster.

The thruster dimensions, 160 mm length x 141mm outer duct diameter, fit the design constraints. The duct is standard Wageningen nozzle no. 19a. The 114 mm diameter propeller offers 161 N bollard pull thrust force at 51 rev/s.

Using the previously mentioned formula we can calculate the thrust coefficient:

$$K_T = \frac{T}{\rho n^2 D^4} = \frac{161 \text{ N}}{999 \text{ m/s}^2 \cdot (51 \frac{1}{s})^2 \cdot (0.114 \text{ m})^4} = 0.36 \quad (2)$$

Several Wageningen Ka series propellers were analysed, each one of them was using Wageningen nozzle no. 19a, the same one as T500 nozzle.

Their respective K_T curves were calculated from the available regression analysis formulae. Total thrust coefficient is the sum of propeller and nozzle coefficients.

Then we translated all the curves to pass through $K_{Total} = 0.36$ (as the calculated one for T500) at $J = 0$ and calculated the average curve. A new curve was drawn, and it was used as an approximation of T500 thrust coefficient. All the curves are presented in the diagram below, Figure 6.

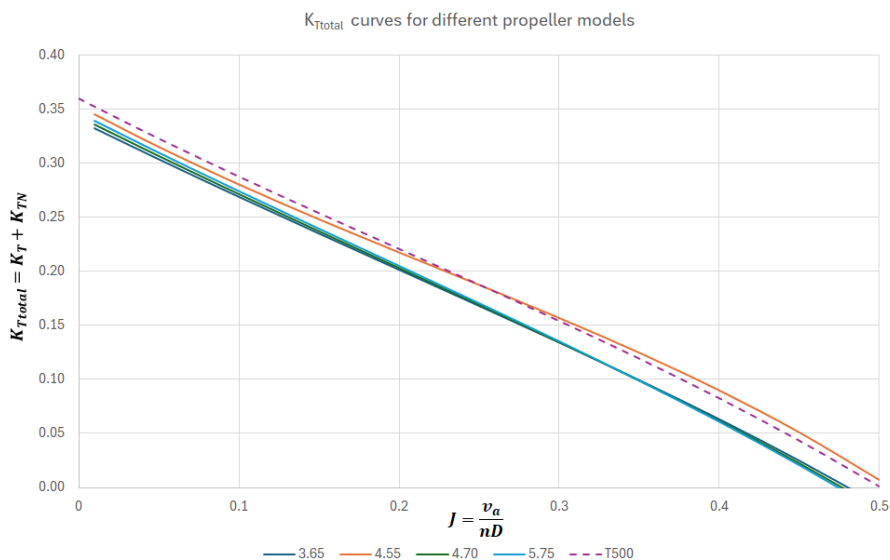


Figure 6. K_{Total} for different propellers.

Since the propeller torque distribution is completely unknown, an approximation was performed using the K_Q curves of the analysed propellers. All four curves were drawn and their average calculated. The average values were then increased by 50% to keep the performance prediction on the safe side. It's expected that K_Q of our propeller will stay well below those values but without any usable torque data for the chosen propeller and a need to decide to continue with the project without the risk of underpowering, the decision was made to use such a high safety margin. In that case the vessel will still be able to reach the required speed just with fewer RPM and lower power needed from electric motor. Update on the method and the margin will be presented after the sea trials. All curves are presented at the diagram below, Figure 7.

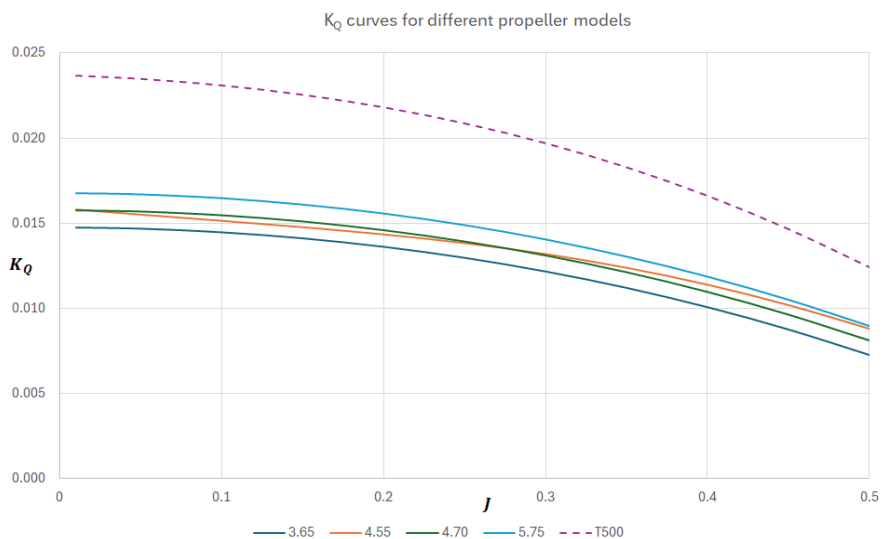


Figure 7. K_Q for different propellers.

Finally, a common propeller data diagram, Figure 8, presented below could be drawn for our propeller. The efficiency on the diagram is calculated as

$$\eta_o = \frac{J \cdot K_{Ttotal}}{2\pi \cdot K_Q}. \quad (3)$$

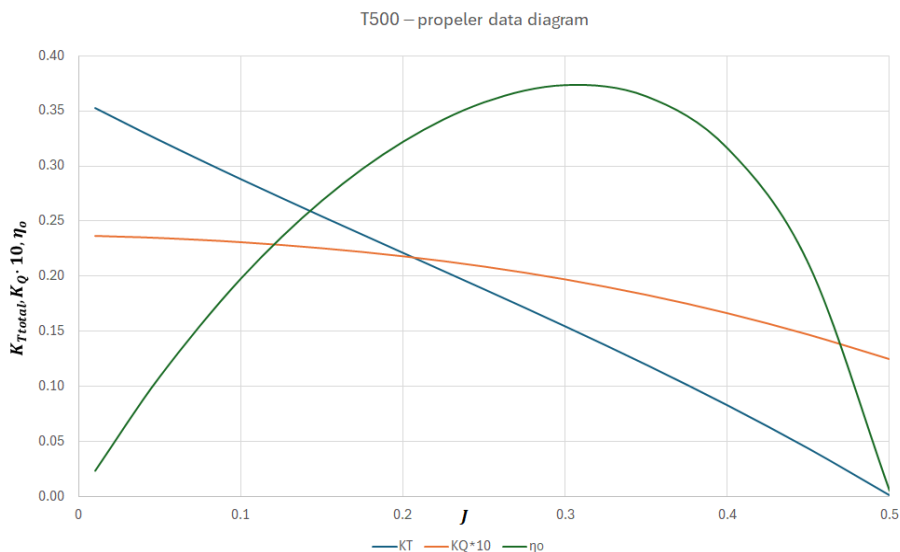


Figure 8. Estimated characteristic of T500 propeller.

A delivered power needed at any advance coefficient can be calculated from the diagram. Values for likely motor working points are presented in the following table and the motor, based on available T500 data, should be able to reach them, Table 4.

Table 4. Motor working points.

J	K_T	K_Q	η_o	n	T	Q	P_D	N
				1/s	N	Nm	W	RPM
0.25	0.188	0.021	36%	70	157	2.0	879	4192
0.3	0.154	0.020	37%	58	90	1.3	480	3493
0.35	0.119	0.018	36%	50	51	0.9	281	2994
0.4	0.083	0.017	32%	44	27	0.6	171	2620

6. Final concept

After a widespread initial design consideration, some narrowing down had to be done to finalize the hull form. Some re-evaluated project limitations and recommendations caused a need to modify the previous concept presented as ASV02 Concept 06a. A final concept and a hull form being produced is ASV02 Concept 07.

Since there will be no hull form changes, this concept will be simply referred to as ASV02 with no additional descriptors in the name.

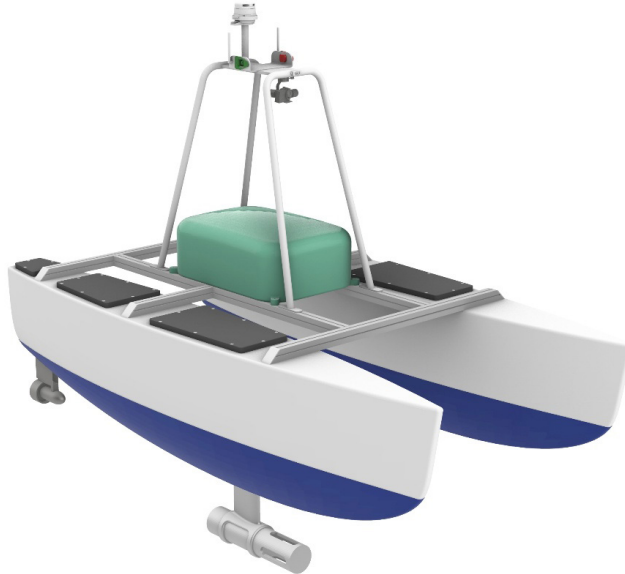


Figure 9. ASV02 equipped model.

6.1. Shorter hull

The major modification was a vessel's length. Boat handling in the workshop, road transport, launching and hauling out were the reasons to make the vessel shorter. Moulds handling also contributed to this decision since they are a little longer than the vessel itself. The hulls are now 2200 mm long which additionally provides flexibility in equipment configurations. For example, outboard motors and/ or rudders can be fitted on the transom or additional equipment protection could be placed in front of a bow, all without a risk of exceeding total length of 2.5 metres, a limitation required by some regulators, Figure 10.

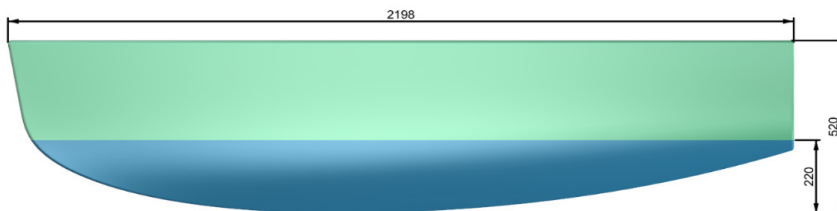


Figure 10. ASV02 hull.

6.2. Fuller hull

Shortening of the hull caused the hull fullness to raise for the hull height to remain the same without changing the displacement. The final design draft is even smaller than the previous one since the fullness was additionally increased to make the vessel less sensitive to weight changes. Previous hopes to make the vessel lighter than 90 kg are hard to achieve and doubts have been raised that even 100 kg is an optimistic assumption. The new deck had to have similar useful area as the previous, longer one so the fulness of the deck outline rose and the transom was made wider. If the need occurs to place the outboard or rudder, vertical transom is a better solution than the slightly angled one in Concept 06a, Figure 11. It's easier to fit and calculate rotations if the environment is vertical.

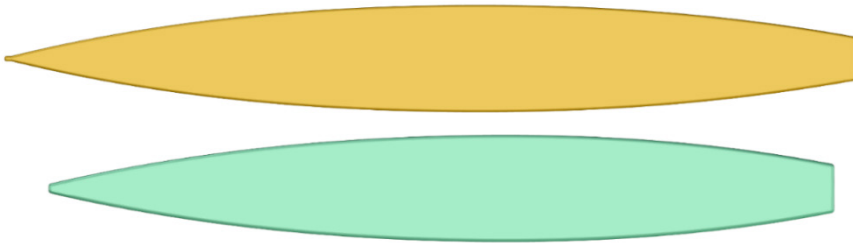


Figure 11. Deck area comparison (Concept 06a above and Concept 07 below).

6.3. Wider keel

A girder keel is obsolete. It makes the lamination of the keel harder and offers too little in return. Potential grip for the underwater equipment support, which was very handy on ASV01 since the whole boat was smaller, can be achieved by fixing those support elements directly to the keel's flat surface, Figure 12. Partially due to the lamination purposes, the keel is significantly wider than the one on ASV01 and offers enough surface for glueing or screwing in any additional piece of equipment.

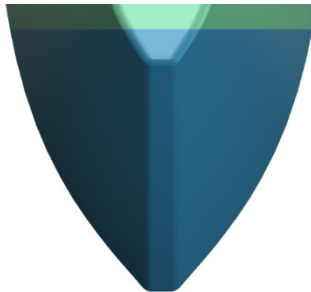


Figure 12. Underwater portion of a hull (viewed from stern) with visible flat keel.

6.4. Motor replacement

Initially chosen motor had to be replaced with another one due to delivery complications. The topology of the new motor is slightly different from the previous one, so the interface with the hull had to be modified, Figure 13.



Figure 13. Motor replacement: (a) 6 TDS10 motor, (b) motor placement.

6.5. Planned experimental validation

Finalised and equipped ASV02 will go through extensive sea testing to validate and update presented calculations and expectations regarding resistance, propeller performance, speed, seakeeping, battery life and reach. Test results will be published in future papers.

7. Conclusion

The development of the ASV02 vessel within the framework of the BRIGANTINE project demonstrates the complexity and challenges of designing small autonomous surface vessels. The process required careful integration of hydrodynamic, structural, mechanical, and operational requirements to ensure stability, low resistance, modularity, and safe operation in both coastal and open-sea environments.

Certain common designing procedures used in ship design were barely usable and other had to be adapted to such a small boat. For the propeller design even a new method had to be developed.

The design evolution, from early conceptual studies to the finalized prototype, revealed the importance of achieving an optimal balance between displacement, hull slenderness, and available propulsion power. The chosen catamaran configuration, lightweight composite construction, and ducted propeller system proved to be an effective compromise between simplicity, performance, robustness and availability.

Future work will focus on the performance verification through experimental testing and on refining the propulsion and control systems to enhance endurance, autonomy, and adaptability for different operational scenarios.

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