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Advance Speed-Hull-Pump-Jet Interactions in Small ASV

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Abstract. This paper is related to the technological development of an innovative small-size Autonomous Surface Vehicle designed to meet the requirement of accessing, monitoring and protecting the shallow waters peculiar of the Wetlands.The first prototype of a fully electric, modular, portable, lightweight, and highly-controllable Autonomous Surface Vehicle (ASV) for extremely shallow water and remote areas, namely SWAMP, was developed by CNR-INM and DITEN-Unige. This catamaran is equipped with four azimuth Pump-Jet Modular (PJM) actuators designed for small-size (1 to 1.5 m long) ASV. The main advantage of Pump-Jet thrusters is that they are flush with the hull, thus minimizing the risks of damages due to possible grounding. This system is used to increase the manoeuvrability in narrow spaces and to increase the spacial resolution by allowing the access also in extremely shallow waters with smaller risk of loosing manoeuvrability. The knowledge of the hydrodynamic characteristics of the thruster and of the vessel allows to partly or fully identifying the vessel for a better controllability. With this aim a series of tests have been conducted in the DITEN towing tank. In particular advance resistance on the SWAMP hull in deep and shallow water, bollard pull and self-propelling tests with the Pump-Jet Module working have been carried out. The results of the tests with the effects of advance speed on the PJM performance is reported in this paper together with the description of the modelling of the thruster itself.

Keywords. Autonomous Surface Vehicles, ASV, Pump-Jet propulsion, Self-propelling tests, Catamaran, Shallow water

1. Introduction

Coastal waters [1], swamps, lakes and rivers with their mouths and deltas and tidal freshwaters [2] are generally known as *Wetlands* and are considered an important natural resource that requires continuous protection and monitoring. Acquiring data to map the ecosystems of wetland and to assess their change over time represents a key step in environmental monitoring. With this aim an increasing number of conventions, directives and research projects work on protection of these ecosystems. Nevertheless the number, quality and spacial resolution of surveys in these peculiar environments is modest due

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to the absence of expressly addressed tools [3,4]. The use of robotic-aided solutions allows to increase the quality of surveys. A new class of reliable, modular, re-configurable, and lightweight Autonomous Surface Vehicles (ASVs) for extremely shallow water and remote areas applications named SWAMP (Shallow Water Autonomous Multipurpose Platform) was built in a collaboration between CNR-INM and DITEN-Unige [5]. SWAMP is a fully electric, modular, portable, lightweight, and highly-controllable ASV. It is a catamaran, equipped with four azimuth Pump-Jet thrusters specifically designed for this vehicle, and characterized by small draft soft-foam, unsinkable hull structure with high modularity and a flexible hardware/software WiFi-based architecture.

In order to combine the ability of working in a few centimeters of water, together with satisfactory control abilities the SWAMP ASV design is based on the use of a prototype of a modular azimuth thruster based on Pump-Jet concept. The Pump-Jet solution has previously been adopted in ships and boats working in shallow waters, but never adopted before in robotic vehicles. Only a small number Autonomous Underwater Vehicles (AUV) [6] adopt a Pump-Jet-like steerable pump-based solution for the manoeuvring of the vehicle and, more recently, a scaled model of ASV [7,8] adopted a steerable grid model of Pump-Jet for a new fleet of self-propelled inland cargo barges.

Vehicles expressly designed to work in shallow and confined waters and in harsh environments can minimize the effects of possible (and probable) impact with the waterway ground by combining a flat bottom with the use of a Pump-Jet-based propulsion unit. Since ASVs must be able to access narrow areas for sampling, even in the presence of external disturbances, they should be fully controllable both in station keeping and in path following. For this reason, a propulsion layout based on four azimuth thrusters (like the Pump-Jet Module) was considered a suitable approach for SWAMP.

In order to increase the controllability of the vehicle a series of tests were performed in towing tank both on the hull, both on the vehicle with the propulsion units in self-propelling condition and in bollard pull. This was useful to increase the knowledge on the Pump-Jet at speed functioning. The results allowed to model and identify SWAMP for a better controlling strategy.

This paper is organised as follows: a brief description of SWAMP is reported together with the Pump-Jet Module and the thrust layout. The testing setup is described and the results of the towing tank tests are reported with a discussion of the results reported.

Figure 1. SWAMP vehicle

2. SWAMP vehicle

As shown in [9] [10] [11] a great number of Autonomous Surface Vessels (ASV) with different capabilities and functionalities was developed, mostly in the last twenty years, arising from academic and research institutions. The growing maturity of robotics makes this technology the most reliable solution for the environmental surveys and recently a relevant number of commercial vessels was introduced in the market demonstrating that ASVs are now a reliable and affordable technology. Nevertheless the few ASVs defined *”for shallow waters”*, are based on existing technologies often not suitable for this peculiar environment. For this reason, on the basis of the requirements described in [12], the vehicle (depicted in fig. 1), whose acronym is SWAMP, was expressly conceived and designed to work in shallow and confined waters. The vehicle is man-portable and transportable by car or in a small boat.

SWAMP is a full-electric Catamaran 1.23 m long with a design breadth of 1.1 m (variable between 0.7 m and 1.25 m). The hull height is 0.4 m and the vehicle with the structure and the antennas is 1.1 m high. SWAMP lightweight is 38 kg with a draft of 0.1 m, the standard maximum payload is 20 kg with a consequent maximum design draft of 0.14 m but the reserve of buoyancy of SWAMP allows to embark up to 60 kg with a draft of 0.22 m. The small dimensions of the vehicle comply with the idea of a reduced logistics. A double ended Wigley-based hull shape was chosen both for hosting four Pump-Jet Module azimuth thrusters expressly designed and studied for this project and to create an innovative structure. Indeed one of the main peculiar aspects of SWAMP is the use of light, soft and impact-survival flexible structure made with a sandwich of soft closed-cell foam, HDPE plates and pultruded bars. This flexible design allows to host various types of tools, thrusters, control systems, samplers and sensors. Also for this reason for the propulsion the choice has fallen on the design of a modular propulsion unit that can be easily installed on the vehicle. The propulsion, as already mentioned, is based on Pump-Jet. Using four azimuth thrusters gives SWAMP the controllability that is required for high quality surveys. As shown in fig. 2 the thrusters were positioned in symmetrical positions on the vehicle two fore and two aft. The Pump-Jet thrusters were built in the CNR-INM labs and tested at various angles and with different configurations. For what concerns the Hardware and Software systems of SWAMP, they consist of a Wi-Fi-based architecture. The hardware architecture of SWAMP is based on COTS components. The basic Navigation Guidance and Control (NGC) package of each hull is composed by an IMU and a GPS. The communication is created by one communication module each hull that provides a communication framework for both its same hull and for the other hull’s modules when its work is required.

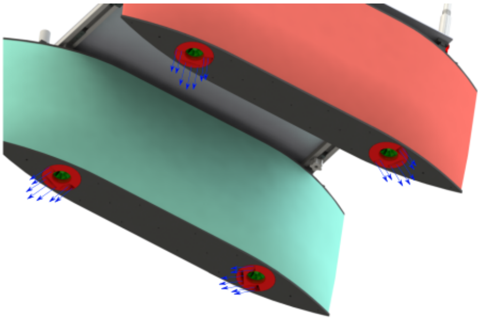

Figure 2. SWAMP bottom view with the flat bottom and the four Pump-Jet Module

The SWAMP hulls were tested, also in shallow water, in the DITEN-UNIGE towing tank at various depth, payload and breadth. Maximum speed of SWAMP in infinite depth waters is 1.6 m/s, while the speed in extremely shallow waters down to 200 mm (i.e. 60 mm of under-keel water) is reduced to 1 m/s due to the change in hydrodynamic characteristics occurring in shallow waters.

2.1. SWAMP hull

The hull shape is inspired by the double-ended Wigley series. A hard balance between conflicting requirements was necessary in the design phase. Among these requirements, good stability, the length to be contained within 1.25 m with a small draft and a high payload of 25/20 kg, the need of fitting Pump-Jets and easiness of prototyping. The catamaran hull was chosen for its good stability. As shown in figs. 2 and 3 the Wigley hull is cut at a certain waterline in order to create a flat bottom suitable to host the Pump-Jet thrusters. The Wigley double-ended hull form and the propulsion layout is characterised by equally efficient sailing ahead and astern with the possibility of manoeuvring in narrow spaces. The wigley hull was chosen also for an easiness to prototype by using expanded foam. In this hull shape the longitudinal centre of buoyancy LCB is centered mid-hull and the hull has large B/T ratios.

As a result the hull values of $B/T = 1.7$, $L/B = 5.1$ and $L/\nabla^{1/3} = 4.1$ of SWAMP result to be small and the bow (and stern) results to be bluff, with a $C_B = 0.67$, if compared to commonly adopted catamarans like those reported in [13,14,15,16] where, usually, when C_B is high the L/B ratio is high too. As a consequence the resistance coefficients of SWAMP is high due to an increased wave resistance.

The operative profile of SWAMP comprises the presence of shallow waters where, sinkage, trim and wave pattern formation around the hull [17] are modified. This depends on water depth h, and in particular on the ratio between water depth and vessel draft: h/T ratio. A substantial reduction in the performances of the vessel in terms of manoeuvrability and resistance is faced. If the h/T ratio is low, then grounding due to excessive *squat* could occur at the bow or at the stern

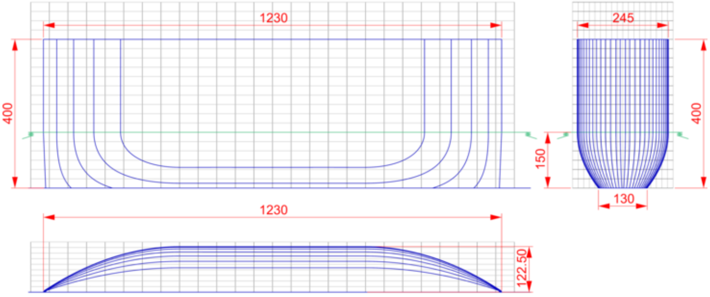

Figure 3. SWAMP hull lines plan

To assess the resistance of SWAMP, towing tank tests were conducted both in deep, and in shallow water.

Towing Tank Tests in deep and shallow waters were performed in DITEN Hydrodynamic Laboratories at the University of Genova. Dimensions are about $60x2.5x3\,m$ with a running distance of $45\,m$ and maximum speed of $3\,m/s$ with capability of measurement of trim and resistance. For the tests in shallow water the carriage was modified and the water in the tank was removed down to the wanted value.

When towing a catamaran like SWAMP,the towing point is placed above the waterline and above the Vertical Centre of Buoyancy VCB. In this case an induced trimming moment is generated and a correction was applied. This was done by using a mobile mass for the correction of the vehicle's initial trim so that the dynamic attitude could be the exact one.

Tests were performed at $h/T = [1.5, 2.0, 2.5, 4.0, 9.0]$. At maximum depth the tests were done at 3 different widths: $B = [820,\ 1100,\ 1250]\,mm$ resulting in $S/L = [0.46,\ 0.68,\ 0.8]$. Test were done at the standard load condition of $58\,kg$ and $T = 140\,mm$. A test was done at the design width of $1100\,mm$ with load condition of $48\,kg$ and $T = 115\,mm$.

In order to evaluate the possible occurrence of channel effect some CFD tests have been conducted during the deep water tests and no occurrence has been recorded. No CFD test was done for shallow water.

From towing tests it was possible to extract the resistance $R = 49\,N$ at a maximum design speed of $1.5\,m/s$ at the maximum loading of the vehicle. The value of $1.5\,m/s$ was considered the reference value to match with the Pump-Jet Module design. From the results reported in a low variability on the resistance depending on the width can be seen with a small interference between the two hulls. Tests at different immersions showed a rough dependence on the wetted surface.

Depth-based tests were performed with the minimum water depth $H = 210\,mm$ with a clearance of $60\,mm$. Test results are reported in fig. 4 where it is possible to see that the resistance substantially increases with the decreasing of water depth and of the H/T ratio..

In particular it is interesting to see that at $H/T = 1.5$ the resistance is about $R = 49\,N$ at $U = 1\,m/s$. The speed loss is of $U = 0.5\,m/s$ if compared to the deep water ($H/T = 9.0$) where the same resistance is obtained at $U = 0.5\,m/s$.

A high squat effect was faced during the tests.

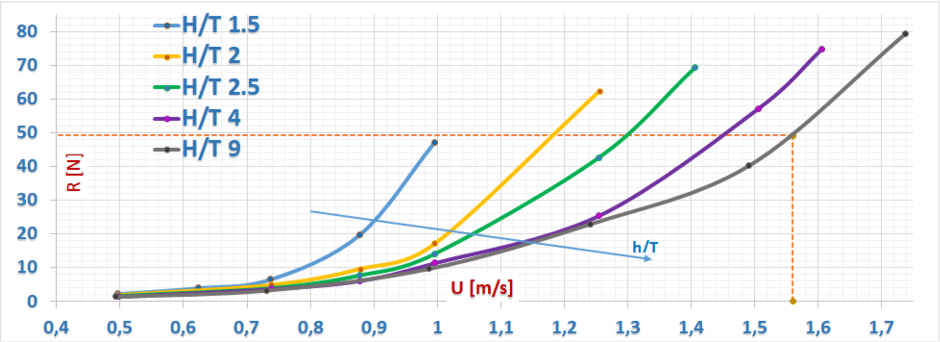

Figure 4. Resistance curves at different H/T, $T = 0.14\,m$ for $S/L = 0.68$

3. Pump-Jet module (PJM)

In this section a brief resume of the concept, design, construction and tests performed on the Pump-Jet Module are reported. A complete description is reported in [18]. The main idea behind the Pump-Jet Module was to design a watertight module that can easily be dismounted from the ASV for easy transportation and can be employed on different vehicles. For compactness, the control unit is embedded and contained inside the module. The azimuth motor provides continuous feedback on position, guaranteeing high maneuverability with high rotating nozzle speed. The entire casing is designed to be 360° steerable.

The main advantage of using PJMs is maximum thrust at minimum draft. It can be used as main thruster and as manoeuvring thruster. The PJM can work in minimum water depths as low as $50\,mm$ without risking damage.

The Pump-Jet operates on the principle of a vertical axis pump. A mixed-flow or centrifugal pump sucks in water from beneath the hull, and through the blades, the water is whirled tangentially and radially outward into the casing chamber. The fluid gains both velocity and pressure while passing through the impeller. The outlet nozzles in the steerable casing accelerate the flow, and a jet of water produces thrust horizontally beneath the flat-bottomed hull. Since thrust is the product of water flow by water velocity then the Pump-Jet requires a very low volume flow to generate a propulsion force. The outlet angle of the water is approximately 15° from horizontal: almost the entire jet thrust is converted effectively into forward thrust.

Concerning the construction, the pump impeller was 3D printed for ease of manufacturing. For the same reason, the module itself was constituted by a 3D-printed element hosting both the inlet duct and the outlet nozzle.

The design based on the theory governing mixed-flow pumps was constrained by geometrical factors (draught, payload, main dimensions), thrust required (giving Pump Head H_p) and RPMs of the chosen brushless motor.

The value of the design thrust for the PJM was obtained from the resistance of SWAMP small-/medium-sized ASVs.

The module may be considered as a free-running propeller studied for bollard pull and low speed. The exact amount of thrust was validated during moving tests where advance speed influences the exact amount of thrust produced by the module resulting into a thrust deduction factor and/or a wake fraction.

The thrust produced by the Pump-Jet system can roughly be expressed as follows: $T\alpha = (\rho_w A_n V_o^2)/cos\alpha_{out}$ with A_n discharge area, V_o outlet flow speed, α_{out} the outlet angle. The design thrust of the Pump-Jet Module was identified as $T = 12.3\,[N]$.

4. Towing tank tests and results

Tests in testing rig

Bollard thrust tests were performed on the 4 Pump-Jet of SWAMP to measure the delivered thrust and power of the impeller using a test rig. This allowed to characterise the propulsion units by defining the thrust vs RPM and the consequent power vs RPM curves that, as far as the control is concerned, results into a driving reference voltage [V] to be applied to the main motor. The four PJM test results at the maximum thrust angle are reported in fig. 5. These tests show a very good matching between all the thrusters results for what regards *thrust vs RPM*.

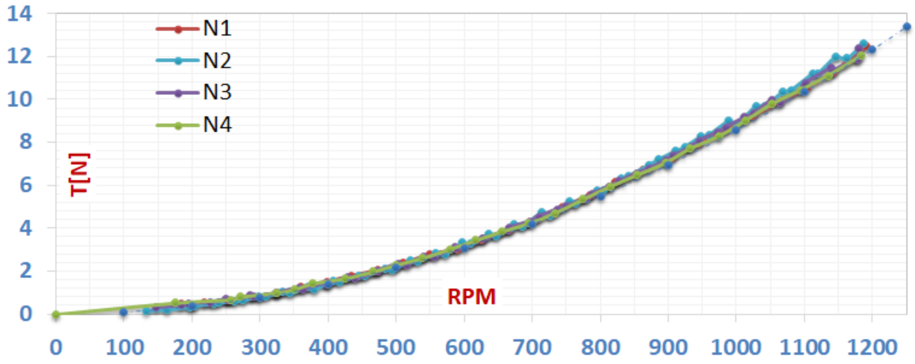

Figure 5. The four Pump-Jet Module bollard pull Thrust vs RPM and Power Vs RPM graphics

Self-propelling towing tank tests

Since no existing result is present in literature then self-propelling tests were conducted in the DITEN towing tank with the vehicle at maximum weight $58\,kg$ and $T = 140\,mm$. Three sets of tests were conducted. i) The first was a towing test with the PJM mounted in the SWAMP hull. This test was necessary to assess the increase in resistance due to the presence of the thruster's hole and to record the resistance necessary for the self-propelling case. Tests were compared with the previous results obtained in the towing tank and no significant difference was recorded. ii) The second test was conducted in bollard pull by using the towing tank dynamometer. This was done by recording the thrust produced by the single thruster and by the thrusters coupled. No significant influence between the thrusters was recorded in static bollard pull tests. iii) The third was a self-propelling series of tests. Each run was recorded three times to ensure no error in the measure was present. Tests were performed in different configurations: a) the four PJMs b) the two fore PJMs c) the two stern PJMs.

Self-propelling test procedure was the following: First a towing tank with 0-rpm was conducted to record a resistance R_0. Then tests were conducted with the RPMs necessary to produce the thrust expected T_{exp} if no thrust deduction was present. Since thrust deduction was present a new non-zero resistance was recorded R_{Rec}. Next a correction to the RPMs was applied in order to reduce the resistance recorded by the dynamometer until the final resistance $R_{fin} \simeq 0$. The thrust deduction was calculated as $(1-t) = \frac{R_0 - R_{Rec}}{n * T_{exp}}$ where n is the number of active PJMs.

Tests were also performed without the zeroing of the thrust in order to record as much as possible points necessary to create the motor speed (RPM) - thrust deduction (1-t) - Velocity (U) surface. In this case the final resistance was $R_{fin} \neq 0$.

The results obtained allowed to produce the characteristic thrust vs advance speed at various motor rotations, as reported in fig. 6 in analogy to the well-known performance charts adopted by all waterjet manufacturers [19].

In fig. 7 the graphic of advance speed vs RPM for the various (1-t) is reported. It is interesting to notice that at low advance speed of $0.5\,m/s$ the (1-t) value is low at lower

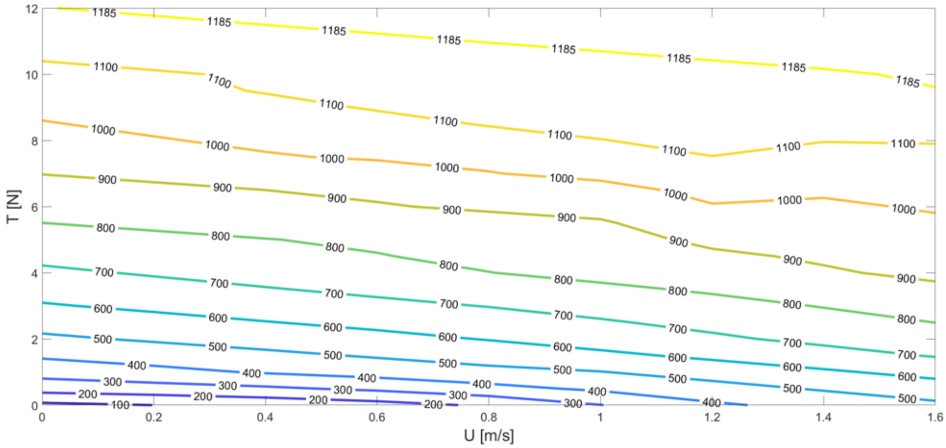

Figure 6. The Thrust [N] vs Speed [m/s] with the level curves representing the various RPMs of the single Pump-Jet Module

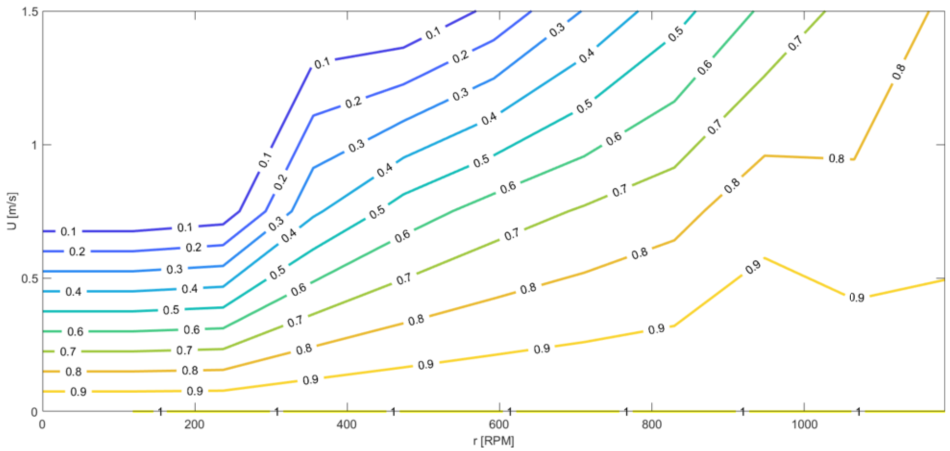

Figure 7. The Speed [m/s] vs RPM at various (1-t) of the single Pump-Jet Module

RPMs while increases as the RPM is increased. This factor is relevant for the controlling strategies since at low advance speed it worth to use two thrusters at higher RPMs instead of four thrusters at lower RPMs. Since a significant increase in the power consumption is recorded. This is true up to when the two thrusters cannot compensate the resistance. In this case a gradual change in the control strategy is required passing from two to four thrusters.

Another interesting point is that the maximum value of (1-t) is obtained at the maximum speed of $1.5\,m/s$ at maximum RPMs of 1185. This (1-t) is around 0.85 which, indeed, is a high value that can be compared to screw propellers. It can be assumed that the Pump-Jet can work well also at higher speeds.

These assumptions are more related to the Pump-Jet. Another assumption is related to the use of the Pump-Jet Module under the SWAMP hull.

As mentioned before, tests were conducted with just a couple of two thrusters working

in fore configuration and in aft configuration. This was done to see whether the position on the hull could influence the thrust value.
Tests were performed from 0.5 to $0.85\,m/s$ and no significant difference was recorded. The difference was at the same scale of the error that was recorded in single test on the single couple of thrusters.

5. Conclusions

This article reported the description of the SWAMP vehicle with a special focus on the propulsion layout. SWAMP is an innovative Autonomous Surface Vehicle that was especially studied for extremely shallow waters down to $200\,mm$. SWAMP installs four new azimuth Pump-Jet thrusters designed for this vehicle. Since the Pump-Jet is installed flush with the hull, it does not produce a significant increase in resistance if compared to other systems, and moreover there is no risk of collision with floating debris. Tests were conducted in the DITEN towing tank at the University of Genova both in towing and in self-propelling.
The results obtained allowed to identify the full advance-speed of SWAMP hull both in shallow and in deep water. Moreover the self-propelling tests allowed to characterise the functioning of the Pump-Jet Module at different advance speed and at different rotational speeds. This gave the possibility of fully identifying the Pump-Jet Module characteristics that are necessary for a good control of the Autonomous Surface Vehicle.
Usually Pump-Jet are used in bigger boats or ships as manoeuvring systems and rarely as main propulsion systems. As a main result of the campaign of tests it was recorded that the effective thrust can be achieved even at higher speeds with a thrust deduction factor that can be compared to the one of screw propellers.
One of the main results is the fact that for the first time extensive tests were conducted on an ASV in towing tank including the shallow waters and the self-propelling. This allows to increase the knowledge of the hydrodynamic characteristics of the ASV for a better controlling strategy.

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