A new concept of highly modular ASV for extremely shallow water applications

Angelo Odetti * **Marco Altosole** ** **Gabriele Bruzzone** * **Michele Viviani** **
Massimo Caccia *

* *CNR-INM, Uos Genoa, Via de Marini 6, Genoa, Italy*
** *DITEN, University of Genoa, Via Rodi 1, Genoa, Italy*
Corresponding author e-mail: angelo.odetti@inm.cnr.it

Abstract: This paper describe SWAMP, a prototype Autonomous Surface Vehicle (ASV) representing the base for the design and development of an innovative class of reliable modular reconfigurable lightweight ASVs for extremely shallow water applications. The design of SWAMP-class ASVs is based on a holistic approach involving different aspects of robotics such as the use of soft materials, the mechanical design of innovative propulsion system integrated with the vessel hull, the adoption of modular mechanical and computing architecture able to support multi-agent distributed GNC systems.

Keywords: ASV, USV, Shallow water, Wetlands, Distributed control, Modularity

1. INTRODUCTION

The research presented in this article focuses on the development of a robotic system for the monitoring of environmental parameters in extremely shallow waters.
Zones like marshes, estuaries, mangroves, ponds, swamps, coral reefs, shallow seas are characterised by shallow waters and are commonly known as *Wetlands*. The Convention on Wetlands, called the *Ramsar Convention* Ramsar (1971), is an intergovernmental treaty that provides the framework for national actions (there are many Ramsar sites in Italy RamsarSites (2019)) and international cooperation for the conservation and rational use of Wetlands and their resources. European Directive 2000/60/EC ”Water Framework Directive”, implemented nationally by the *Environmental Consolidation Act (Testo Unico Ambientale)* Decree (2006), establishes a framework for ’Community action in the field of qualitative and quantitative water protection for the implementation of a sustainable long-term use and protection policy for all inland waters (surface and underground), for transitional waters and for coastal marine waters’. The priority objective is to maintain good water status, protect and improve the conditions of aquatic ecosystems, Wetlands and terrestrial ecosystems, in consideration of their need for water. The Environmental Consolidation Act has, for the first time in Italy, introduced the obligation for regions to systematically monitor the coastal ecosystem. This means that the authorities are obliged to implement monitoring programs to assess the achievement or otherwise of a good environmental status, consequently adopting the actions and measures necessary to achieve the objective set by the directive. In this framework Wetlands need to be continuously monitored or mapped but these are generally not easily accessible (also for the presence of shallow water). This makes it difficult to collect the adequate amount of data. In some cases data are not available or not sufficiently updated or with a low resolution. In the past, long and expensive investigation with manned ships or other inappropriate methods where necessary to collect the minimum amount of data thus showing the lack of appropriate solutions.
The lack of a hydrographic vessel capable of performing shallow water measurements at depths of less than 1 m has led to unreliable maps and data, thus motivating research on innovative technical approaches for executing the tasks of water sampling, limnological surveys, bathymetric analyses and monitoring of water quality. In recent years a variety of robotic approaches to improve the quality, speed, and accessibility of surveys have been explored by research groups using both commercial and ad-hoc solutions.
In this paper a prototype Autonomous Surface Vehicle (ASV) named SWAMP (Shallow Water Autonomous Multipurpose Platform) is proposed as the base for an innovative class of reliable modular re-configurable lightweight ASVs for extremely shallow water applications. SWAMP class ASV will also be able to support, as test-bed, research on cooperative distributed mechanical and GNC systems as well as innovative technological solutions in terms of materials, sensors and actuators. The paper is organised as it follows. Section 2 discusses technical requirements, basic operational configurations, and the consequent design parameters of the platform. The design of a modular catamaran, based on a couple of mono-hull vessels, characterised by double-ended hull made by lightweight soft foam, is presented in section 3, The SWAMP’s innovative

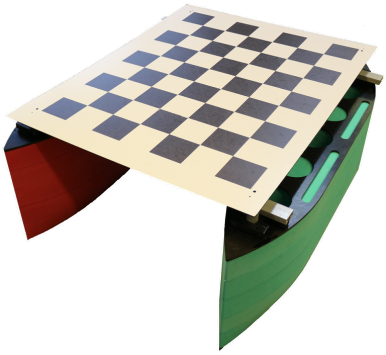

Fig. 1. SWAMP (Shallow Water Autonomous Multipurpose Platform)

pump-jet propulsion system is introduced in section 4, while sections 5 and 6 shortly describe the vehicle power supply and computing systems.

2. VEHICLE DESIGN PARAMETERS

Following the increasing interest in the construction of ad-hoc solutions to improve the efficiency and effectiveness of Wetlands monitoring the authors designed an ASV which characteristics were influenced by specifications of different missions. The ASV design is based on the hints described in Odetti et al. (2018) taking inspiration on the operational requests from operators of Italian public and private bodies that usually monitor Wetlands and shallow waters and from practical experience of CNR-INM marine robotics group. The latter has a long experience with ASV design and exploitation. *ALANIS* boat has been developed for coastal monitoring Caccia et al. (2009), Charlie is a catamaran used for bathymetric surveys Bibuli et al. (2014) and sampling in Antarctica Caccia et al. (2007), while the semi-submersible vehicles *Shark* and *PROTEUS* have been used for sampling in dangerous areas in front of Arctic Tidewater Glaciers Zappala et al. (2016), Piermattei et al. (2017), Bruzzone et al. (2018).
Technical specifications for the ASV for monitoring surface water bodies were identified in:

- General arrangement: Modularity, flexibility and reconfigurability.
- Manoeuvrability, Controllability: floating platform with enhanced manoeuvring ability and a high capacity of adapting to the various type of missions such as repetitive tasks, efficient scan, sampling in specific spots, pre-programmed trajectories.
- Standard dimensions suitable for hand transport and Panel van transport. Transportability is one of the main parameters in harsh environments
- Draft contained since dealing with shallow waters the maximum draft is a fundamental parameter to be
- The propulsion should be adequate to access in extremely shallow waters without the risk of damages with consequent loss of the vessel
- Impact ability: hull structure, the system of propulsion and the sensors supports suitable for harsh environment and hard transport
- Navigation mode: the vehicle should be remotely controlled within a range up to 2000 m. Autonomous use with pre-set route and remote control should be implemented. Wi-Fi and/or radiomodem communication systems have to be provided. Telemetry has to be recorded in a data logger.
- Payload: a basic payload will be composed of two cameras (one infrared (IR), allowing night view) and live viewing during operations from the control station on the shore, either an Inertial Motion Unit (IMU) or an Attitude and Heading Reference System (AHRS) and an RTK-GPS system for precise data acquisition, altimeter, communication system and data logging of basic parameters such as air temperature, surface water temperature and sensor of wind direction and intensity. The vehicle will have an open both hardware and software architecture and it will thus have the ability to easily mount different payloads and in manifold working configurations.

In harsh environment the peculiar aspect of surveys is that the robots adopted should be re-configurable to permit the operators to adapt the various need coming from at field operations. Mainly four different possible scopes of SWAMP were identified:

- Multi-parameter monitoring platform composed of a deployable underwater multi-parameter probe and air parameters probe possibly deployable with an aerostat.
- Sampling platform with a surface water sampling system or with an underwater sampling system to be deployed and significantly contributing to the final total weight of the vehicle.
- Morpho-bathymetric platform with different kind of sensors to be mounted in the hull under free water surface or in direct contact with water. These are used for bed mapping and monitoring also for the monitoring of Posidonia meadows in coastal areas Ferretti et al. (2017).
- Aerial drone landing and take-off platform: it requires the presence of enough space for the take off and landing of an aerial multi-copter drone whose dimensions are contained.

Most of the requirements suggest the presence of a wide main deck on the top of the vehicle. Also for this reason a catamaran hull shape is the most suitable solution. A catamaran shape is also advantageous since allows to reduce the draft by maintaining high payload. The vehicle resulting from the above mentioned requirements is *SWAMP (Shallow Water Autonomous Multipurpose Platform* and is shown in Fig.1. The ASV is expressly designed to work in shallow and confined waters and in harsh environment and its hull geometry is influenced by the need of hosting the peculiar propulsion unit expressly designed for shallow waters which name is Pump-Jet Module. SWAMP is a full-electric vehicle $1.25m$ long with a variable breadth between $0.8m$ and $1.25m$. The two hulls of SWAMP are designed to be double-ended to enhance the controllability of the vehicle. Its lightweight is approximately $35kg$ with a draft of $0.1m$ and the design-maximum-payload is $25kg$ with a consequent design-maximum-draft of $0.15m$. For minimising the effects caused by an impact with the waterway ground then the bottom of SWAMP is flat as shown in Fig.2. This hull configuration is studied both for hosting four Pump-Jet type 360° azimuth thrusters and to create an innovative structure that also avoids the presence of sharp edges on the hull bottom. Indeed one of the main peculiar aspects of SWAMP is the use

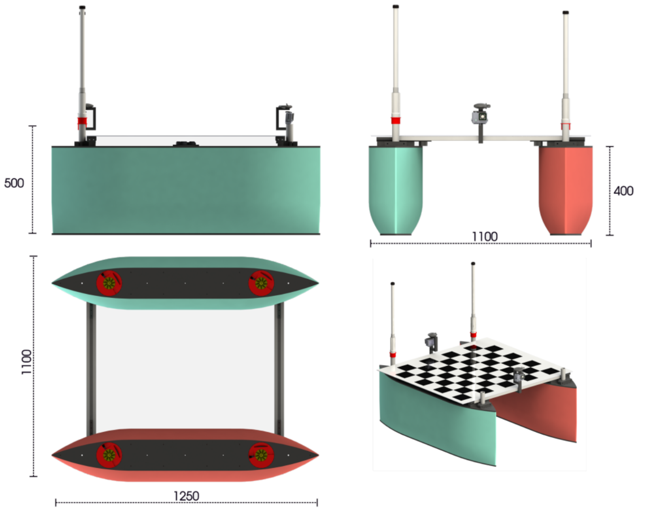

Fig. 2. Vehicle general layout with measures

of a light, soft and impact-survival flexible structure made with a sandwich of flexible closed-cell foam, High Density PolyEthylene (HDPE) plates and pultruded bars. Thus SWAMP is a completely modular catamaran able to host various types of tools: thrusters, intelligent systems, samplers and sensors. For this reason the choice was to design all the parts of the vehicle as modular elements that could be easily installed on the vehicle. Such a solution allows also to remove, if necessary, some of the thrusters and/or substitute them with sensors and/or tools. As an example in deeper waters it is possible to substitute the Pump-Jet Module with another thruster if, as an example, more thrust is required.

The geometric characteristics of SWAMP are reduced immersion, controllability, propulsion intactness even in shallow water and minimal effect on the environment. The minimum water depth is 200 mm and the vehicle is adequate to work also in these extremely shallow waters without the risk of damages; the possible impact of the vehicle on outcropping stones, roots or similar objects that can damage both sensors and the propulsion system with consequent risk of loosing the vehicle is minimised with the structure and the geometry studied.

The main concept adopted for the design of SWAMP was the development of a new vehicle characterised by a complete modularity where all the components of the vessel cannot be considered as ”characteristics” of the vessel but as tools installed on the vehicle. The catamaran is composed by two hulls that can be considered as one single vehicle. Each hull has its intelligent core, its propulsion unit(s), its power and its communication. All the elements inside the single vehicle is connected via WiFi to the central core but none of them can be considered as ”definitively” present on SWAMP, even the central core. This concept is an extreme application of modularity that should lead to a vehicle that can be modified at every application.

3. HULL AND STRUCTURE

As mentioned before and as shown in Fig.2 SWAMP is a Catamaran ASV with double-ended hulls. Catamarans allow to have much more payload space than on mono-hulls, they are more stable, have smaller draft with higher payload and the presence of thrusters on each hull gives the possibility of well manoeuvring in narrow space with agility. Achieving a good stability was the main driver in the choice of the Catamaran shape since payload elements like sonars used for mapping the bottom request for stable platform with less motions. Another point in this direction was the possibility of having a wide payload area suitable for modularity and re-configurability.

The main idea behind the choice of double-ended hull was the possibility of coupling this solution with the adoption of four azimuth thrusters to be adequately manoeuvrable also in restricted waters and in presence of external disturbances.

Modularity was one of the main ideas behind the conception of this kind of structure. Every hull is composed of various transverse sections of lightweight foam which number or shape may be modified in function of the actual needs. In this way the hull geometry may be modified to increase the volume and reduce the immersion or to augment stability or to reduce the drag or in function of other operational requests.

This concept also allows to think the hull as a modular structure where propulsion units, batteries in a various number, sensors and payloads may be positioned or removed from the hull.

The vehicle is constituted by the two mono-hull vehicles and the two connection bars. Payload like winches, samplers, sensors, landing pads etc.. can be installed on the payload deck. The final weight of the entire catamaran structure is 15 kg.

To find a good matching between controllability, hull integrity, portability, payload requirements and hydrodynamic performances.

The hull was designed with the mathematical formula of Wigley hulls. This is a simple and easy to model shape that was adopted also to reduce the construction time. The single hull is 1.24 m long, 0.24 m wide with a maximum draft of 0.14 m and a block coefficient of $Cb = 0.67$. Tests were performed in DITEN Hydrodynamic Laboratories towing tank to measure the resistance of SWAMP. The Towing Tank is provided with dynamometric carriage with capability of measurement of ship trim and resistance.

As far as stability is concerned SWAMP catamaran shape is advantageous thanks to the unique characteristics in terms of stability. The total width of catamaran is larger than equal mono-hull resulting in better transverse stability.

4. PROPULSION: THE PUMP-JET

A propulsion module has been expressly designed for shallow waters based on the Pump-Jet concept. The propulsion unit was developed as a Pump-Jet module (Pump-Jet Module) to be installed on the vehicle in an ease way. The main advantage of Pump-Jet system is the fact that this propulsion is flush with the hull as shown by the section reported in 3, thus minimising the risks of damages due to possible grounding. Pump-Jet operates on the principle of a vertical axis pump: an impeller sucks-in water from below the hull and through this gains both velocity and pressure. The water is directed to an external volute and pushed towards outlet nozzles present in the 360 deg steerable casing. The nozzles accelerate the flow and a jet of water produces thrust horizontally beneath the flat-bottomed hull.

A propulsion layout adopting four azimuth thrusters one bow and one stern on each hull and coupled with a double-ended hull shape was chosen to seek high controllability and manoeuvrability of both the catamaran that, in this way, has a redundant system both on the single hull.

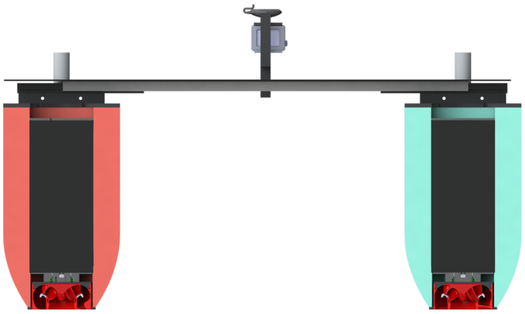

Fig. 3. SWAMP section with the view of the Pump-Jet Module

The propulsion unit was designed, modelled, constructed and tested in the CNR-INM laboratory.

5. POWER

Power is provided by two batteries, one each hull with a Voltage of 36 V and with a capacity of 13 Ah each. With the above mentioned resistances and in a standard mission its is possible to foresee a usage of the vehicle for 6 hours in standard configuration. With this power supply a standard mission can be constituted by a transfer speed of 1 m/s and an operational

Table 1. Standard Mission

U $[m/s]$	$time$ $[h]$	P_{prop} $[W]$	P_{tot} $[Wh]$
1	0,5	80	85
0,7	5,5	41	655
1	6	80	85

speed of $0.7\,m/s$: Additional power batteries may easily be installed on-board of SWAMP.

6. HARDWARE CONTROL SYSTEM

The hardware control system of the SWAMP vehicle is fully modular and it is based on a set modules contained in watertight canisters. These modules contain computational boards, sensors and actuators for the control of the vehicle while, as shown above, batteries for power supply are housed into different canisters. Each module composing the hardware control system has got only one connection used for power supply and communicates with the other modules by means of a WiFi radio link at 2.4 GHz. Each of the two hulls composing the complete SWAMP vehicle has got (at least) three modules:

- computational module
- actuation module
- communication module

The computational module is based on a Raspberry Pi 3.0 model B SBC (Single Board Computer) running the Raspbian OS (Operating System), IMU (Inertial Motion Unit) providing absolute orientation (yaw, pitch and roll), angular velocities and linear accelerations and a GNSS (Global Navigation Satellite System) position sensor. The computational module of each hull, by means of the WiFi link, can communicate with the computational module of the other hull (e.g. for coordinating their maneuvers), with its actuation module and, by means of the communication module, with the pilot console.
The motors with corresponding encoder with the controllers are installed in the modular Pump-Jet.

7. GUIDANCE AND CONTROL SYSTEM

A conventional multi-layered Guidance and Control architecture will be adopted.
The Guidance module handles vehicle's kinematics, executing tasks such as path-following, station-keeping, auto-heading and speed, by computing linear and angular velocity references for the Control module, that, handling vessel's dynamics, computes reference forces and torque in a vehicle-fixed coordinate system.
The Thrust Control Mapping module has to determine the optimal thrusts and orientations of the four SWAMP's pump-jets in order to generate the desired force and torque. As shown in Fig.2 the Pump-Jet Module thrusters are positioned on SWAMP inside holes machined in HDPE foam plates. Through the structure the forces are transmitted to the hull. With azimuth thrusters there are infinite configurations of the thrust vectors for every task being station-keeping, path-following or auto-heading and speed. With this configuration the system results redundant respect to a complete failure of one or more thrusters.
The Thrust Control Mapping module has to establish the optimal control strategy: for instance, the four thrusters can be supposed to work at the same time for propulsion when dealing with high speed or around the critical Froude Number when operating in shallow waters, while in low-speed operations two thrusters can be supposed to work for main propulsion and the others for manoeuvrability. For station-keeping, thrust allocation strategies can be taken into consideration with different goals like the minimisation of the power consumption or the minimisation of number of thrusters used. It is worth noting that each hull hosts a complete control system, thus paving the way to the use of SWAMP's as a test-bed for distributed cooperative guidance and control of mechanically-linked vessels.

8. VALIDATION

For the identification and validation of the vehicle various tests were performed in DITEN facilities. Moreover a mathematical model was developed in Matlab®for the simulation of the dynamics of the model and the testing of control algorithms.
Hydrodynamic tests were performed in DITEN Hydrodynamic Laboratories towing tank to measure the resistance of SWAMP. The Towing Tank is provided with dynamometric carriage with capability of measurement of ship trim and resistance. Various tests were performed on SWAMP to characterise the vehicle in its different operational situations.

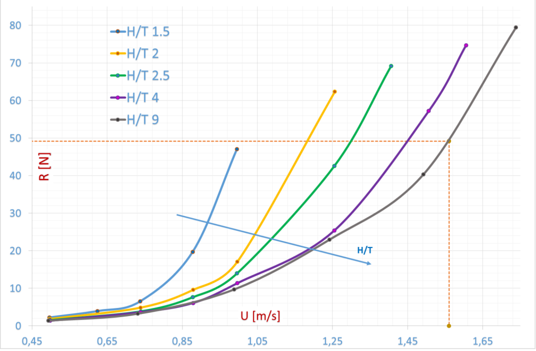

Fig. 4. Resistance curves at different H/T

Tests were performed in deep water at three different catamaran breadth B and at two different loading conditions and in shallow water at different water height resulting in different ratio (h/T) between water depth and vessel immersion : $h/T = [1.5, 2.0, 2.5, 4.0, 9.0]$.
These were important since any vessel navigating through restricted and shallow waters is heavily affected by hydrodynamic effects. In these zones proximity effects occur causing increasing in resistance and errors in maneuvering which can lead to grounding or collision. The most common effect is caused by the lowering in pressure (Venturi effect) occurring between the bottom of the hull and the waterway bottom that sinks the vehicle and usually causes a secondary effect called *squat effect*. This effect happens when the vehicle trims aft or bow in a manner usually different from the one happening in deep waters. If the h/T is low, then grounding due to excessive squat could occur at the bow or at the stern. In SWAMP case full scale tests were conducted in the DITEN facility by emptying the tank. The results of both the deep and shallow water tests are reported in Fig.4 and show the effect of shallow water on vehicle resistance. This effect is higher at lower h/T and shows how important is the increase in resistance that reduces the possible velocity of about $0.5\,m/s$.The validation of the propulsion unit together with the design, modeling and construction was conducted at the CNR-INM laboratory. The final tests results are reported in 5. The four thrust unit were tested by using

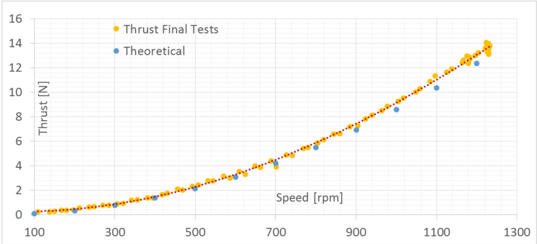

Fig. 5. The results of the Pump-Jet tests reported with the theoretical curves

a specific test-rig that showed that all the Pump-Jet Module behave in the same way. More details on this are reported in Odetti et al. (2019).

A simulator to describe SWAMP manoeuvrability was developed able to consider all the operational situations of the vehicle. SWAMP is studied to work at full speed and in slow motion (e.g. in station keeping). To take into account both the operational cases it was necessary to adopt a model where the hull forces could be used in all the conditions. These include 0 and low speed and higher speeds (1.5 m/s) that means Froude numbers from 0 to 0.4. For the open sea navigation a great number of mathematical models based on experimental and theoretical approaches that allow the manoeuvrability to be well predicted exist. However, for low speed, there are still few works and the high speed models cannot be applied since the coefficients often diverge. The solutions are few (some including CFD simulations as Villa et al. (2019)) but one simple model is the one proposed in Yoshimura et al. (2009) and based on the *MMG* (described also in Yasukawa and Yoshimura (2015)) that was adopted for SWAMP. In the model the characteristic of course stability and initial turning is kept the same as the conventional mathematical model, and it is considered so that the conventional database can be easily applied. Considering the vehicle as a rigid body with three degrees of freedom: two translations, the forward motion along the longitudinal axis x_{0G} and the drift motion along the transverse axis y_{0G}, and the rotation ψ about the vertical axis (Yaw). Being u,v and r the forward, drift and rotational speeds of the body in the body fixed coordinates system and Δ and I_{zz} the mass constants.
Coupling the rigid body equations in earth fixed and body fixed system with the equilibrium equation the global forces and moments acting on SWAMP are a sum of external disturbances (wind, current, waves), internal forces of the hull and a sum of forces ($X_{thrusters}$, $Y_{thrusters}$) and moments ($N_{thrusters}$) produced by the thrusters:

$$\begin{cases} X = X_{Hull} + X_{Propulsion} + X_{Current} + X_{Wind} \\ Y = Y_{Hull} + Y_{Propulsion} + Y_{Current} + Y_{Wind} \\ N = N_{Hull} + N_{Propulsion} + N_{Current} + N_{Wind} \end{cases} \tag{1}$$

The manoeuvrability equations used by Yoshimura et al. (2009) are the same as the *MMG*:

$$\begin{cases} (M - X_{\dot{u}}) \cdot \dot{u} = M \cdot (v \cdot r + x_G \cdot r^2) + X \\ (M - Y_{\dot{v}}) \cdot \dot{v} + (M \cdot x_G) \cdot \dot{r} = -M \cdot ur + Y \\ -(M \cdot x_G) \cdot \dot{v} + (I_{zz} - N_{\dot{r}}) \cdot \dot{r} = -Mx_G \cdot ur + N \end{cases} \tag{2}$$

Where, since the steady hydrodynamic force is proportional to the square of fluid velocity, the basic structures of hydrodynamic force components of vessel hull (X_H, Y_H and N_H) are basically described as the sum of products of velocity components (u, v and r). For the specific application, knowing the possible uncertainties that this may lea, the coefficients were adapted to be applied to a catamaran model.
As far as the thrust is considered, given τ_i as the generic thrust always positive and $\alpha_i = (0, 2\pi]$ the generic angle and thrust configuration of SWAMP can be seen in Fig.6 The thrusters forces acting on SWAMP are then reported on the local coordinates system of the vehicle and summarised as:

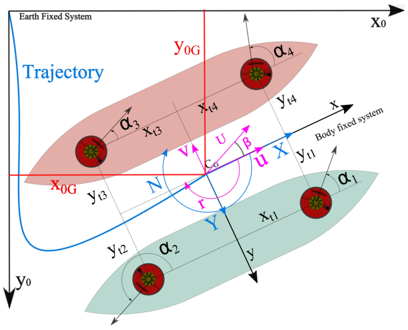

Fig. 6. The reference system for the thrust allocation of SWAMP vehicle

$$\begin{pmatrix} X_{thrusters} \\ Y_{thrusters} \\ N_{thrusters} \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{pmatrix} \tag{3}$$

Where:

$$T_{1i} = cos\alpha_i$$
$$T_{2i} = sin\alpha_i$$
$$T_{3i} = y_{t_i} cos\alpha_i + x_{t_i} sen\alpha_i$$

A Matlab model was implemented to validate the mathematical model and various simulations where done to check the absence of singularities.
An example of the simulations performed is reported in Figures 7 to 10. To the model is applied a control system that maps the same thrust (direction and intensity) to the stern thrusters to perform a $-20deg$ to $+20deg$ zigzag test. An external disturbance is applied to the vehicle by means of the bow thrusters controlled in the same direction and intensity ad randomly activated. From the tests it is possible to see how the vessel returns to produce a zigzag path with the same main heading.

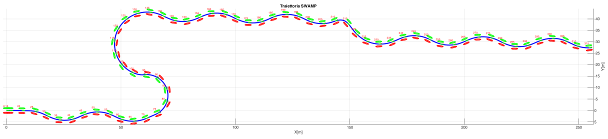

Fig. 7. The simulated SWAMP trajectory in a zigzag test

9. CONCLUSIONS AND FUTURE DEVELOPMENTS

The paper presents the prototype of an innovative class of reliable modular re-configurable lightweight ASVs for extremely shallow water applications. The proposed solution is based on a holistic approach involving different aspects of robotics such as the use of soft materials, the mechanical design of innovative propulsion system integrated with the vessel hull, and the adoption of modular mechanical and computing architecture able to support multi-agent distributed GNC systems. The resulting prototype SWAMP is characterised by extreme modularity

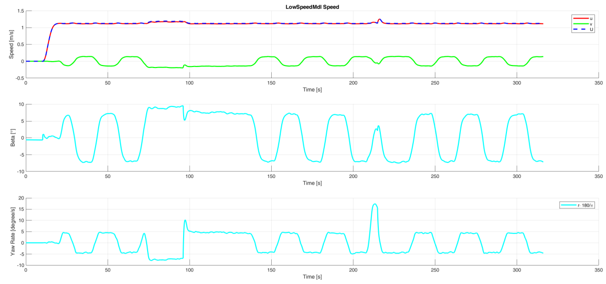

Fig. 8. The zigzag simulation velocities u,v,r and the angle β

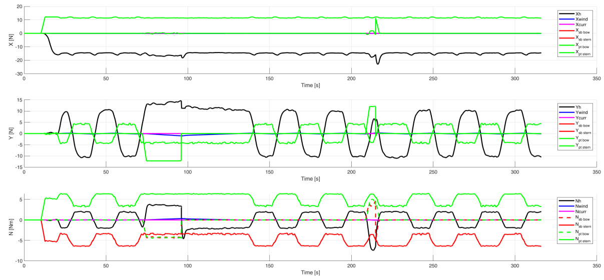

Fig. 9. The forces acting on SWAMP in the zigzag simulation in x,y $(X_{ith} Y_{ith})$ and the moment about z $((N_{ith}))$

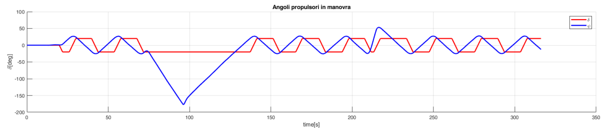

Fig. 10. The angle of thrusters (δ) and the yaw angle(ψ) in the zigzag simulation

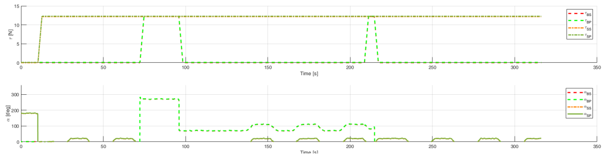

Fig. 11. The four thrusters thrust-vector components in terms of thrust (τ) and angle(α

and re-configurability, where the foreseen distribution of power batteries in each actuator, sensor, and computing module, as well as the use of on-board WiFi communications will lead to the design of a cable-free vessel able to support research in distributed cooperative control systems under soft and rigid mechanical links.

10. ACKNOWLEDGMENTS

This article is part of the Ph.D work carried on at DITEN University of Genova by Angelo Odetti in the framework of the XXXII Cycle of the Ph.D in *Scienze e Tecnologie per l'Ingegneria Elettrica, l'Ingegneria Navale e i Sistemi Complessi per la mobilità*. Special thanks go to Giorgio Bruzzone, Giuseppe Camporeale, Mauro Giacopelli, Edoardo Spirandelli, Marco Bibuli, Roberta Ferretti and Enrica Zereik of CNR-INM and to Alberto Ferrari, Diego Villa and Sergio Talocchi of DITEN Unige.

REFERENCES

Bibuli, M., Bruzzone, G., Caccia, M., Fumagalli, E., Saggini, E., Zereik, E., Buttaro, E., Caporale, C., and Ivaldi, R. (2014). Unmanned surface vehicles for automatic bathymetry mapping and shores' maintenance. In *OCEANS 2014-TAIPEI*, 1–7. IEEE.

Bruzzone, G., Odetti, A., and Caccia, M. (2018). Remote data collection near marine glacier fronts - unmanned vehicles for autonomous sensing, sampling in the north pole. *Sea Technology*, 59(3), 22–26.

Caccia, M., Bibuli, M., Bono, R., Bruzzone, G., Bruzzone, G., and Spirandelli, E. (2007). Unmanned surface vehicle for coastal and protected waters applications: The charlie project. *Marine Technology Society Journal*, 41(2), 62–71.

Caccia, M., Bibuli, M., Bono, R., Bruzzone, G., Bruzzone, G., and Spirandelli, E. (2009). Aluminum hull usv for coastal water and seafloor monitoring. In *OCEANS 2009-EUROPE*, 1–5. IEEE.

Decree, I.L. (2006). 152/06. *Testo unico ambientale. Modificato e integrato con il d.lgs. 4/2008 e con il d.lgs. 128/2010.*

Ferretti, R., Bibuli, M., Caccia, M., Chiarella, D., Odetti, A., Ranieri, A., Zereik, E., and Bruzzone, G. (2017). Towards posidonia meadows detection, mapping and automatic recognition using unmanned marine vehicles. *IFAC-PapersOnLine*, 50(1), 12386–12391.

Odetti, A., Altosole, M., Caccia, M., Viviani, M., and Bruzzone, G. (2018). Wetlands monitoring: Hints for innovative autonomous surface vehicles design. *Technology and Science for the Ships of the Future. Proceedings of NAV 2018: 19th International Conference on Ship and Maritime Research*, 1(1), 1014–1021.

Odetti, A., Altosole, M., Bruzzone, G., Caccia, M., and Viviani, M. (2019). Design and construction of a modular pump-jet thruster for autonomous surface vehicle operations in extremely shallow water. *Journal of Marine Science and Engineering*, 7(7), 222.

Piermattei, V., Madonia, A., Bonamano, S., Martellucci, R., Bruzzone, G., Ferretti, R., Odetti, A., Azzaro, M., Zappalà, G., and Marcelli, M. (2017). Application of a low cost instrumentation in arctic extreme conditions. In *4th International Electronic Conference on Sensors and Applications*. Multidisciplinary Digital Publishing Institute.

Ramsar (1971). *Convention on Wetlands of International Importance especially as Waterfowl Habitat*. Director, Office of International Standards and Legal Affairs., UNESCO. UN Treaty Series No. 14583. As amended by the Paris Protocol, 3 December 1982, and Regina Amendments, 28 May 1987.

Ramsar-Sites (2019). `https://www.ramsar.org/sites-countries/ramsar-sites-around-the-world`.

Villa, D., Viviani, M., Gaggero, S., Vantorre, M., Eloot, K., and Delefortrie, G. (2019). Cfd-based analyses for a slow speed manoeuvrability model. *Journal of Marine Science and Technology*, 1–13.

Yasukawa, H. and Yoshimura, Y. (2015). Introduction of mmg standard method for ship maneuvering predictions. *Journal of Marine Science and Technology*, 20(1), 37–52.

Yoshimura, Y., Nakao, I., and Ishibashi, A. (2009). Unified mathematical model for ocean and harbour manoeuvring. In *International Conference on Marine Simulation and Ship Maneuverability*.

Zappala, G., Bruzzone, G., Caruso, G., and Azzaro, M. (2016). Development of an automatic sampler for extreme polar environments: first in situ application in svalbard islands. *Rendiconti Lincei*, 27(1), 251–259.