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U-SWATH
The innovative CNR research USV

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Abstract. This paper describes U-SWATH an innovative Unmanned Surface Vehicle (USV), based on a Small Waterplane Area Twin Hulls (SWATH) design, developed by CNR INSEAN and ISSIA for institutional research purposes. The vehicles is composed of a wide flat deck covered with solar panels which connects two torpedo hulls. The hulls are composed of modular and interchangeable sections that can be outfitted with different payloads, equipments, propulsive or manoeuvring elements. The propulsion system is based on ad hoc electrical azimuthal thrusters. The solar panels covering the wide U-SWATH bridge are used for recharging the batteries supplying power to the vehicle. U-SWATH is multitasking and the goal of the designers was to develop a cutting-edge autonomous multi-purpose platform for carrying out research in the marine and the maritime fields.

Keywords. Unmanned Marine Vehicles, SWATH, Marine Robotics, Hydrodynamics, Unmanned Surface Vehicles

1. Introduction

In the framework of the RITMARE Italian Flagship Project, CNR INSEAN and ISSIA developed U-SWATH (Unmanned-Small-waterplane-area twin hull), an innovative Unmanned Marine Vehicle (UMV) for institutional research purposes.
The RITMARE Flagship Project [1] is one of the National Research Programmes funded by the Italian Ministry of University and Research. RITMARE, coordinated by the CNR, was the leading national marine research project for the period 2012-2016 and involved an integrated effort of most of the scientific community working on marine and maritime issues, as well as some major industrial groups.
This project aimed at integrating all the marine sciences by creating links between Observation Systems for the Mediterranean Marine Environment, Coastal Waters and Open Sea Marine Environment, Fishing, Marine and Maritime Technologies, Research Structures and Marine Data Network.
Innovative projects as RITMARE are a way to strengthen the strategic presence of the Italian research in Europe and in the Mediterranean.
In this framework a way to connect technological aspects with the requirements of the monitoring of Marine Environment is the development of innovative autonomous marine

vehicles. Autonomous robotics is progressively expanding and modifying the capabilities in exploration and monitoring of the oceans and coastal areas. The use of autonomous marine vehicles has nowadays become a common practice in applications such as geological prospecting in the oil & gas sector, and oceanographic monitoring, as well as in the military sector. Autonomous marine vehicles [2], whose use is often still limited by

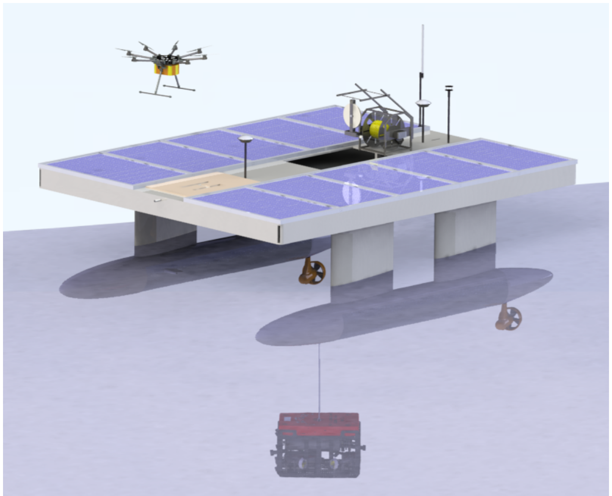

Figure 1. Representation of U-SWATH in operation

the regulatory framework, greatly increase the performance of the surveys by allowing more precision, the reduction of execution times and also to carry out specific operations in protected, difficult or dangerous environment [3].
CNR ISSIA and INSEAN developed U-SWATH in order to integrate skills in naval engineering, ICT and robotics and other innovative aspects of CNR research. U-SWATH is an Unmanned Surface Vehicle, able to work both in coastal and inland waters to carry out surveillance, monitoring and sampling operations and one of its main purposes is to be used as a test-bed for research and technological development activities in areas such as: naval architecture, robotics, marine sciences, material technologies and research on innovative power systems.

2. U-SWATH layout and structure

U-SWATH is an autonomous surface vehicle belonging to the category of Small Waterplane Area Twin Hull, better known by the acronym SWATH. The submersed twin-hull ship design minimizes hull cross section area at the sea's surface making the vehicle very stable in water.
U-SWATH design is studied into a two submarine hulls connected to the upper platform by a couple of twin narrow struts from each of the submarine hulls (for a total of 4 struts). The SWATH non-conventional design, already successfully used by a small ASV [4] and theorized in a bigger version by [5], was chosen to fulfil the design specifications of having a high stability and a reduced resistance. Infact this configuration minimizes hull

cross section (related to wave generation) with reduction of energy consumption and increase in survey time. Even if the small variation of restoring hydrodynamic contribution could not guarantee a perfect sea-keeping for vertical motions, the excellent transversal stability, even in high seas and at high speeds allows an optimal use of underwater mapping instruments.
For the purpose of hull optimization U-SWATH hull has been simulated by means of numerical simulation tools as in [6] in fresh water and salt water conditions in compliance with ITTC standards.
Different type of simulations have been made both in steady state and unsteady state with wave resistance analysis. Among these the simulations some took into consideration of the second twin-hull (for the interference factor analysis) and the propulsion system.
U-SWATH with its 5 m in length and 4 m in breadth is considered a huge dimension

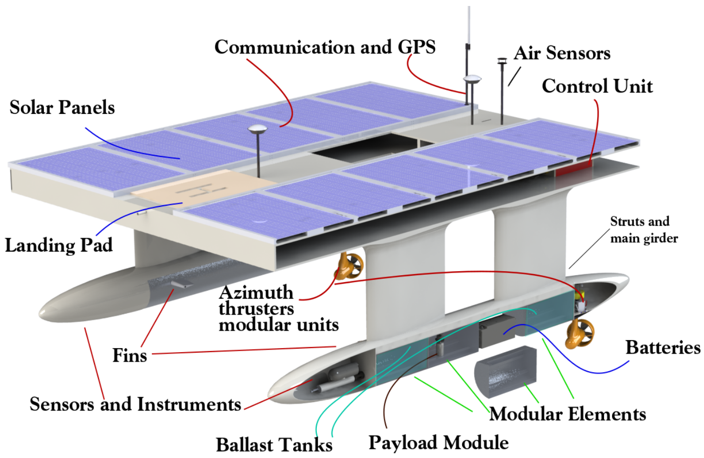

Figure 2. U-SWATH General Layout

vehicle if compared to existing civil ASV. The maximum weight of the vehicle is around 1500 kg, of which 600 of payload. These important dimensions ensure a high degree of modularity, a huge number of possible payload and the capacity of working even with higher sea states. Each of the submersible hulls, connected to the bridge via two vertical struts one in the bow and the other in the stern, is composed of a main supporting girder and six cylindrical interchangeable modules. Every module is waterproof and can be easily modified and/or changed to be outfitted with different payloads, equipment, propulsive or manoeuvring elements, as shown in Figure 2. This is a very good way to satisfy the need for modularity for the submerged parts.
U-SWATH is mainly constructed in anodized aluminium but all the non-structural parts are realised in plastics. The wide space resulting from the SWATH design is exploited by the construction of a flat bridge constituted by a rectangular watertight box with an exposed area of approximately 15 m^2. This is covered with solar panels supplying power to the batteries and in the future it will be able to host a solar sail.
The whole structure of U-SWATH is intended to be modular and the intelligent core of the vehicle too. It is contained in a plastic canister positioned inside the box-shaped anodized aluminium deck. This communicates and interact with the manifold sensors and actuators already installed on the vehicle and others that could be installed at a later time.

Table 1. U-SWATH, Unmanned Small Waterplane Twin Hull characteristics

Main Characteristics			**Power and Electronics**		
Length L	$[m]$	5.0	Rated Power	$[kW]$	2.5
Breadth B	$[m]$	4.0	Autonomy	$[h]$	8
Height H	$[m]$	1.5	Batteries 12 V, 70 Ah	nr	8
Weight	$[kg]$	1400	Solar Panels	15 m^2	200 W/m^2
Maximum Draft	$[m]$	0.75			
Rated Speed	$[m/s]$	3			
Azimuthal Thrusters	nr	2			
Propulsion Unit Thrust	$[N]$	250			
Navigation Payload			**Scientific Payload**		
Double antenna GPS	Trible		Echo Sounder	Tritech	
LED Lights	nr 4		CTD Probe	Idronaut	
Analogic Cameras	nr 3				
Doppler velocity log	Teledyne				
IMU	Microstrain				
Air Direction Sensor	WindSonic				

These comprise Navigation and control systems, Communication, survey sensors and instrumentation.
The propulsion of USWATH is based on two new azimuthal thrusters especially developed for U-SWATH and installed in the stern module.
Four automatic ballast tanks located inside 4 modules, 2 per hull, will be used for the balancing of depth and trim.
According to the trend of recent and current European projects, such as CADDY [7], where robots can cooperate with other underwater vehicles or with man operators, one of the main innovations introduced by U-SWATH is the possibility of autonomous docking of UAV (aircrafts) and UUV (submarines). Aerial drones can take-off and land from the bridge thanks to the good stability of the SWATH design and the wide cargo space that guarantees a good landing area. An appropriate winch positioned on the bridge (see Figure 1) allows the release and recovery of objects in water and can be used for Launch and Recovery of Remotely Operated Vehicles (ROV) like e-URoPe [8] (also developed in the framework of RITMARE flagship) connected with a tether to U-SWATH. The adoption of these solutions creates the basis for Marsupial robotics [9] where a mother vehicle (U-SWATH in this case) becomes the base for release and recovery of other smaller unmanned marine vehicles, an important task for the extension of marine surveys to air and underwater.
The vehicle is mainly designed for different purposes: monitoring of waters, chemical-biological analysis, emergency or patrolling.
The wide space present on-board both underwater inside the modular hulls and on top and under the box bridge make U-SWATH a suitable multi-purpose platform where researchers of CNR and other institutions will be able to perform their experiments: a laboratory for bio-chemical measurements, for testing of new materials, motors, propulsion systems, stabilizing control surfaces, optical and electromagnetic instruments, new sensors or study of hydrodynamic noise.
The possibility of hosting other mechanisms for the extraction of energy from wind and waves and currents will also be evaluated.

It is from these needs that U-SWATH originates, trying to improve and increase the adoption of large vehicles for autonomous surveys, services and research.
The U-SWATH modular payload concept arises from the requirement of multitasking and interchangeability in the long period. For this reason even the propulsion system is modular as well as the ballast tanks and the battery modules.
The planned typical duration of the missions carried out by U-SWATH is 8 hours and the maximum speed is 3 m/s for transfers, while it is 1 m/s or even less during the phases of monitoring and measurement.

3. Azimuthal thrusters modules

The new propulsion unit for U-SWATH was developed by ISSIA (mechanics and electronics) and INSEAN (ducted propeller).
Two azimuthal thrusters are used for both thrust and manoeuvring with a pod that can rotate around a vertical axis (azimuth) allowing a higher degree of manoeuvrability than a fixed propeller and rudder system. The podded system, standing underneath the hull, works in undisturbed free-stream thus increasing the efficiency.
The unit is similar in the concept of ABB Group's Azipod [10] where an electric motor is fitted in the pod itself, connected directly to the propeller without gears.
The propulsion units are placed underneath the stern modules as shown in Figure 2. In figure the design of the thruster is shown.
Each thruster electromechanics consists of a main motor positioned inside the pod with its corresponding support, an azimuth motor and the electronics of control all embedded in the system thus constituting a real unique module.
The support is constituted by a stainless steel plate supporting a housing containing bearings, azimuth shaft and gearbox, the azimuth motor, the support for the azimuth motor and the electronics of control for the main motor.
The main motor, chosen from preliminary resistance, is a 48V brushless motor with 1 kW at 1300 rpm. For safety reasons the on-board tension is kept at 48 V or below, since a 48V underwater brushless motor 1 kW, was not present in the market we decided to design a new motor with an AISI316 case and a double sealing with an oil compensated protection in collaboration with Servotecnica.
The azimuth motor is a stepper motor with integrated electronics, encoder and driver. A 3:1 gearbox reduction with two lub-less and maintenance free plastic gears provides a torque of 21.2 Nm at 8.6°/s. This torque is used for manoeuvring the active system given by the main propeller directionality and passive system given by the vertical element connecting the main electric motor to the mechanical casing which is a Naca wing profile rudder.
The cables of the main motor pass through the vertical shaft. On the cable side a pouring of resin and double O-ring coupling are used to seal the internal from external, a slip-ring on top of the vertical shaft guarantees the electrical connection through the continuous rotation of the propulsion unit. In order to guarantee high performances the whole mechanics has a high degree of precision.
As mentioned before we have two different operational speed, the transfer speed is 3 m/s and the operative speed is 1 m/s.
The azimuthal ducted propeller has been designed at free running condition, through

numerical models. The prototype performances have been measured in different layouts and testing conditions through open water tests in calm water and at zero yaw angle [11]. The azimuthal ducted podded propulsor has been considered as the best choice. In fact such a configuration ensures safety (preventing propeller damages in shallow water condition), efficiency, reduced noise and is satisfactory in terms of the enhanced manoeuvring capabilities required. The adoption of a nozzle around the propeller increases performances at low speeds (here, 1 m/s).

A two stage design process has been applied. An empirical model has been used to define the base ducted propeller configuration, whereas a modified version has been identified through the application of a hybrid RANS/BEM model for modified geometries at the design point [12]. Results of the design process are shown in Figure 3 in terms of performances of an existing ducted propeller series, of numerical prediction through RANS/BEM-based simulations and ofs the resulting propulsor model. The INSEAN

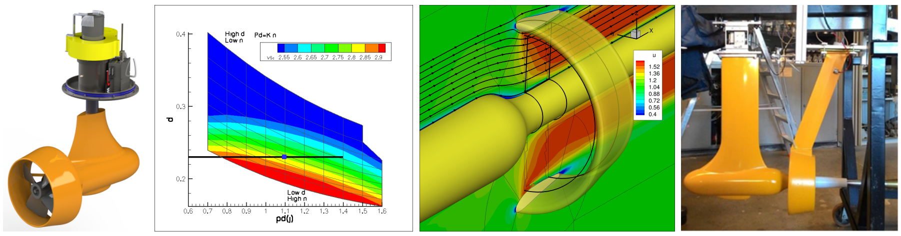

Figure 3. U-SWATH Propulsion unit design process: mechanical design, definition of configuration, RANS/BEM simulation, test rig

E1648 model propeller with a P/D=1.1 inside the 1922d0 nozzle is derived from the Wageningen Ka4-70 in nozzle 19A [13]. The complete propulsion unit have been tested by means of open water tests in calm water and zero yaw angle; the experimental set-up, Figure 3, enabled the measure of the single load contribution which provides the total thrust and torque. A comparative analysis of the different configurations has been performed for a given propeller submergence. Performances are enhanced at low speeds in presence of the accelerating duct around the propeller, whereas the pod represents a passive body over operative conditions. A complete description of the experimental activity can be found in [11]. The experimental measures of the hydrodynamic efficiency of dif-

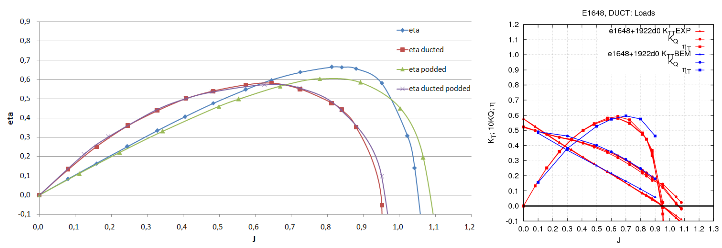

Figure 4. Propulsive performances in open water condition of different propulsive configurations

ferent propulsive configurations and the numerical(BEM)/experimental comparison of the ducted propeller loads are shown in Figure 4 for a wide range of operative conditions.

4. Power and electronics

For safety reasons the on-board maximum tension is kept under 48 V. Power is supplied by a system of eight 12 V and 70 Ah batteries positioned inside one module per hull and recharged by an endothermic generator before the mission and by a system of 48 V solar panels disposed on the surface of the bridge during the mission. Solar Panels have a total exposed area of 15 m^2 and are characterised by a 200 W/m^2 power density that can generate up to 3.5 kWh.
Power and Communication to the underwater modules is guaranteed by a series of LAN and 48 V cables that are redistributed inside each module in relation to the power and communication needs of every single module's payload.
The control system of U-SWATH is installed in a waterproof box located inside the bridge and it is based on a SBC (Single Board Computer) and two PC/104 modules providing digital input/output, analog input, analog output and serial input/output respectively. All these I/O channels permit the SBC to communicate and interact with the manifold sensors and actuators already installed on the vehicle and others that could be installed at a later time. The sensors that will be initially mounted on board U-SWATH and used for basic navigation are: compass, GPS, IMU and altimeter. Further expansions, foreseen in a near future, will provide: a multi-beam sonar, a side-scan sonar, a RADAR and a LIDAR for obstacle detection and avoidance, a Doppler Velocity Log, a Fiber Optic Gyrocompass. The box inside the bridge also contains the DC-DC converters used for powering the control system and a wired Ethernet link used by the control system for communicating with the data acquisition and control systems of the equipment that will be located on the modules placed on the hulls. As far as the communication systems are concerned, U-SWATH is equipped with two Wi-Fi Ethernet links working at 2.4 GHz. One Wi-Fi communication channel is devoted to send commands to and to receive telemetry data from a remote operator, the other Wi-Fi channel is made available for the payloads. An additional radio channel at a lower frequency (169 MHz) and narrow bandwidth but with a longer operating range is used as a security link. Also an acoustic modem is be installed on board for communicating with underwater equipment (e.g. ROVs, AUVs, moorings, etc.) Finally, an Ethernet IP camera (whose video stream will be sent through the Wi-Fi Ethernet link) is mounted in the bow for allowing FPV (First Person View) remote piloting. Some additional IP camera can be mounted both laterally and in the stern either for facilitating manoeuvring operations or for observing the surrounding environment

5. Guidance and Control

The employment of new concept hulls and thrust configurations as Small Waterplane Area Twin Hull (SWATH) combined with Azimuthal propulsion (common propeller-based thruster with the capability of 360 rotation around the vertical axis), requires robust guidance techniques to provide precise and reliable motion control during navigation. The developed apporach is based on a dual-loop guidance & control scheme able to provide advanced navigation capabilities. In particular, the inner control loop, devoted to the actuation of the azimuthal thrusters, allows the tracking of reference course angle (namely the autopilot). Such a control loop is characterized by a modified PID regulation scheme, where a novel adaptive derivative component is inserted in order to improve the convergence curve towards the required course reference. The outer guidance loop, based on Lyapunov/virtual-target approach, allows the vessel to track generic desired paths, thus enhancing the autonomous navigation capabilities also in constrained environments. The global stability of the guidance scheme ensures the path reference tracking also under disturbed operative conditions, i.e. waves, wind and current.

6. Payload and expected mission

As mentioned before U-SWATH is intended as a research vessel for CNR institutional research. A CNR internal call-of-interest identified several possible applications of the vehicle.
The first application is coastal monitoring and environmental parameters analysis also in protected areas and with innovative solutions which may include:
Seabed mapping with Multibeam echo sounders, reflection seismic systems, GPR, etc also in hardly accessible areas; Laboratory for bio-chemical type measures with analysis of pollutants in critical areas; Environmental monitoring of air and water parameters with with CTD, ADCP (Current Doppler Current Profilers), thermometers , etc also for time-varying Oceanographic processes; Biological analysis with Zooplankton sampling systems, DNA sampling systems and other Biosamplers; Analysis with Optical sensors based on auto-fluorescence in UV or Raman scattering will be tested for the detection of pollutants like hydrocarbons, Biological oxygen Demand (BOD) or Dissolved Organic Matter (DOM); Analysis of acoustic spectrum obtained by means of a single-beam echosounder working at double frequency for posidonia mapping; First emergency monitoring for oil-spill; Sea state, surface currents and seabed monitoring with X-band radar data with possible detection and tracking of targets and oil spills on the sea surface; Use of Fiber optic sensors for monitoring o deformations and/or temperatures over long distances (up to 1km); Hydrodynamic noise measurement.
As a test-bench U-SWATH will be used for various innovative researches:
Testing of new materials like super-hydrophobic, antifouling and anticorrosion coatings; Testing of new engines; Testing of alternative energy systems for wind and wave energy extraction; Testing of new propellers; Testing of new stabilizers; Testing of new control surfaces; Testing of new optical and electromagnetic; Testing of new sensors; *Structural health monitoring* of U-SWATH with feasibility analysis of energy recovery systems from on-board vibrations.
U-SWATH Operational research application may include:
Loading on board a CNR research vessels to be used in remote areas; Docking of AUV (aircraft) with docking and recharging station; UUV (underwater) launch and recovery; Forming a bridge of communication between various vehicles and the mother ship or the land-

7. Conclusions and next steps

U-SWATH is a base for future exploitation of marine sciences, for the development of robotics and can become the base for future improvements in the national and interna-

tional research programs. Future steps of the project foresee the model identification with PMM, in the presence of waves and the validation at field of hydrodynamics. This will include tests of the boat at Nemi Lake and at sea.
Future Challenges are various: cooperation between heterogeneous Unmanned Vehicles (UxV) like USV for take-off and landing platform for a UAV and launch and recovery of a Remotely Operated Vehicle; driving and control in adverse conditions like waves and wind; adaptive sampling and real-time analysis of data and samples for the on-line rescheduling of the mission.

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